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MARCH 1978

Advanced Energy Systems Division

NUCLEAR BI-BRAYTON SYSTEM FOR AIRCRAFT PROPULSION STUDY

FINAL REPORT

CONTRACT F33615-77-C-0116

PREPARED FOR
THE UNITED STATES AIR FORCE
AIR FORCE SYSTEMS COMMAND
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AFB, OHIO 45433

WESTINGHOUSE ELECTRIC CORPORATION
Advanced Energy Systems Division
P.O. Box 10864
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Parametric and reference system definition studies were performed with respect to a new concept for a nuclear aircraft propulsion system. Also studied was a possible method for increasing the payload of a nuclear powered aircraft during wartime.

The Bi-Brayton system concept for nuclear propulsion of aircraft has been examined and found to be feasible. The system has been shown to be one over

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20. ABSTRACT (Continued)

which minimizes the component developments required and one which can make effective use of reactor technologies that already exist. Cycle variants and component characteristics were parametrically evaluated and a reference system defined. Weight estimates indicate that with optimized reactor and shielding, the total powerplant and fuel weight for the Innovative Aircraft Design Study Task II reference aircraft could be reduced from that predicted for a NuERA liquid metal cooled reactor system coupled to an open Brayton cycle turbofan engine. The Bi-Brayton system combined with a compact gas-cooled (NERVA derivative) reactor was found to be a desirable system for nuclear aircraft propulsion and is recommended for consideration in any further studies of nuclear propelled aircraft.

Concepts for a removable containment vessel were defined as a possible method of enhancing payload. Although removal of the vessel was not judged to be attractive, the fundamental idea of enhancement of paylaod under special conditions was judged to have merit. Other possible methods for payload enhancement were identified.

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1.0 INTRODUCTION

This report presents the results of a study of a new concept for a nuclear aircraft propulsion system and of a possible method for increasing the payload of a nuclear powered aircraft during wartime conditions.

During recent studies of nuclear aircraft propulsion systems (such as the Reference 1 U. S. Air Force Innovative Aircraft Design Study (IADS) Task II and the Reference 2 U. S. Navy Nuclear Powered Air Loiter Aircraft Study) and Westinghouse funded in-house studies, a number of propulsion cycles and systems were identified. One of the more promising system concepts was the Bi-Brayton system, shown in Figure 1-1, because of its potential for reduction in system weight and its elimination of the need for a very high temperature intermediate heat exchanger.

Another concept with the potential for weight reduction noted during the IADS was that of a containment vessel which could be removed during wartime conditions when crash safety issues may be secondary to mission accomplishment with maximum payload.

This study examined both the Bi-Brayton cycle and the removable containment concepts in sufficient detail to define system sizes, weights and performance characteristics. The study includes a preliminary definition and evaluation of the Bi-Brayton cycle utilizing an advanced high temperature gas-cooled reactor. It also includes an identification of advanced technology requirements which are not expected to occur without specific Air Force development efforts.

These Bi-Brayton system study efforts did not include definition and design of the nuclear reactor. For that input to the study, Westinghouse made available the necessary results from in-house studies which defined the advanced gas-cooled NERVA (Nuclear Engine, Rocket Vehicle Applications) derivative Light Weight Nuclear Propulsion (LWNP) reactor (Reference 3, 4 and 5).

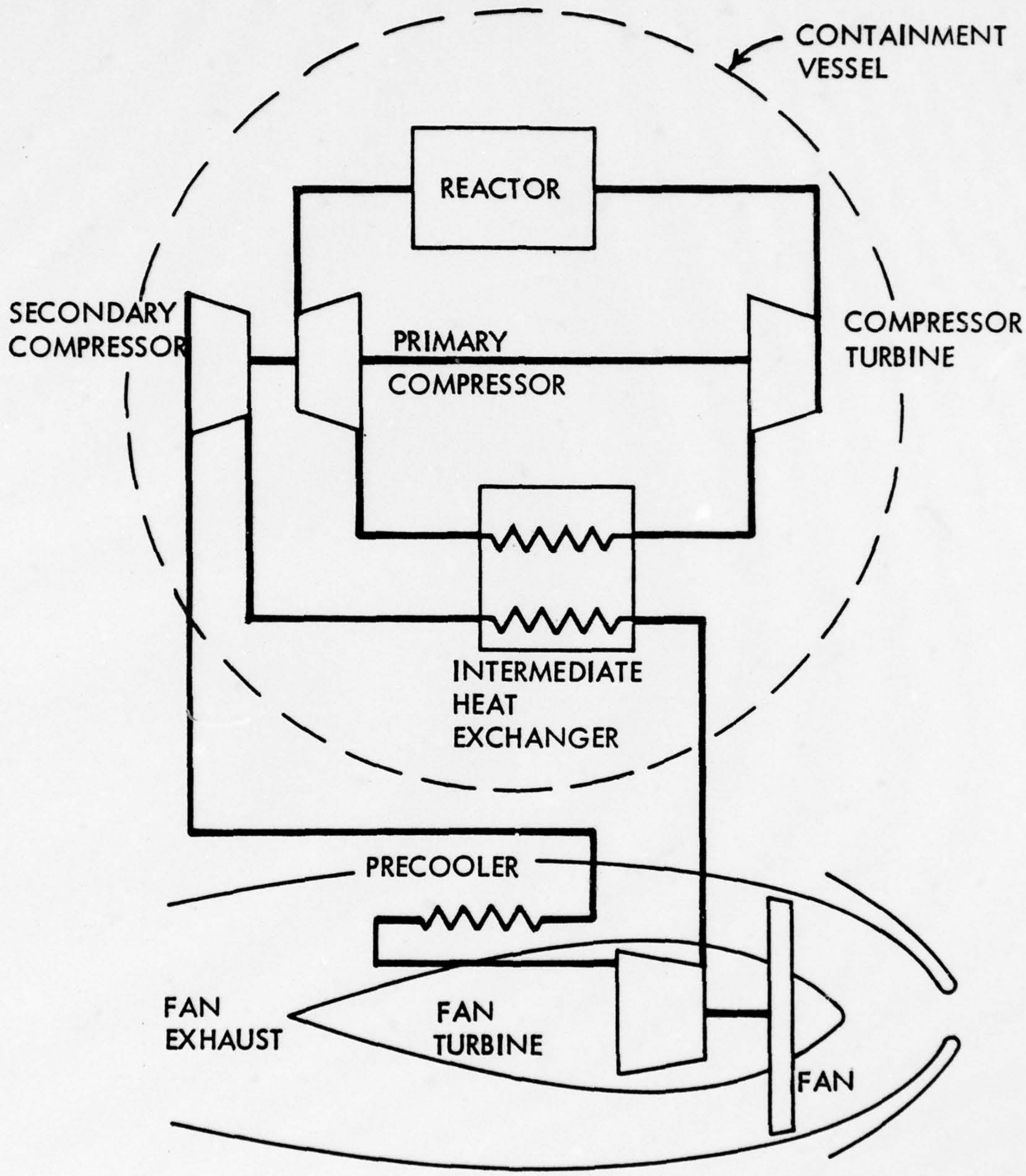

Figure 1-1. Bi-Brayton System Schematic

The examination of the removable containment vessel concept was limited to conceptualizations of means of achievement and assessments of the worth and difficulties. In addition, consideration was also given to identification of other means to enhance payload capability in wartime.

This study was performed under the guidance of Dr. L. W. Noggle, the Air Force study manager. The study was accomplished by the Westinghouse Advanced Energy Systems Division with Mr. R. E. Thompson as Project Manager. Contributors included:

R. Calvo
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2.0 SUMMARY AND CONCLUSIONS

2.1 SUMMARY

The Bi-Brayton system concept for nuclear propulsion of aircraft has been examined and found to be feasible. The system has been shown to be one which minimizes the component developments required and one which can make effective use of reactor technologies that already exist. Cycle variants and component characteristics were considered in establishing a representative reference cycle. Nuclear Subsystem weight versus power characteristics were derived. Weight estimates with unoptimized reactor and shielding indicate essentially the same propulsion system total weight as for the NuERA propulsion system in the IADS Task II reference aircraft application, and indications are that optimization will show propulsion system weight reductions. The Bi-Brayton system combined with an advanced gas-cooled (NERVA derivative) reactor is very attractive and should be considered further in any future studies of nuclear propelled aircraft.

Concepts for a removable containment vessel have also been defined and examined as a means of enhancing wartime military payload capability. Although removal of the vessel was not found to be attractive, the fundamental idea of enhancement of capability in wartime was deemed to have merit. Other possible methods of enhancement of capability were identified.

2.2 CONCLUSIONS

1. The Bi-Brayton system coupled with an advanced gas-cooled (NERVA derivative) reactor is a feasible system for aircraft propulsion.
2. The Bi-Brayton system has the advantages, compared to other nuclear systems studied in recent times for aircraft, of significantly reducing the difficulties in:
   a. The intermediate heat exchanger
   b. The reactor development

c. The intermediate piping

d. The engine heat exchanger

e. The associated JP fueled open cycle engine.

3. The Bi-Brayton system, coupled to a NERVA derivative gas-cooled reactor with unoptimized shielding, has been estimated to have the same total power plant and fuel weight as the reference IADS Task II NuERA system. Reactor and shielding optimization will reduce the total weight by 10 percent (75,000 pounds). It is recommended that the Bi-Brayton system at the lower weight be used in future aircraft studies.

4. The Bi-Brayton system has been found to allow latitude for use of off-optimum component designs in order to ease development problems, if they should occur, without excessive performance penalty.

5. The Bi-Brayton system could make effective use of higher helium turbine inlet temperature capability without greatly increasing the other Bi-Brayton system component developments required.

6. Although costs were not examined in detail, the costs of a Bi-Brayton system are judged to be less than those derived for a liquid metal system in the Innovative Aircraft Design Study, Task II.

7. The technology developments that would be necessary were identified. The possibility exists for much of the turbomachinery and reactor developments to be accomplished by other than the Air Force or for common development programs by the Air Force and Navy.

8. The concept of a removable containment vessel to enhance military payload capability in wartime was judged to be unattractive, but other methods of enhancing payload were identified.

9. It is recommended that more detailed definition study of the Bi-Brayton system and components be accomplished to provide the data base necessary as input to aircraft studies. Specifically, optimization of reactor, shielding and overall nuclear subsystem configurations for the Bi-Brayton aircraft system are recommended to define the lower weight that should be used in aircraft studies. Other recommended studies are discussed in Section 5.4.

3.0 REFERENCE CONDITIONS

The reference conditions specified by the contract task statement were based on the reference design conditions of the Innovative Aircraft Design Study, Task II (Reference 1). Use of these conditions therefore allows the Bi-Brayton study results to supplement the Reference 1 results. Use of these conditions also permits direct comparison of the Bi-Brayton system study results with the Reference 1 results obtained using a liquid metal cooled NuERA (Nuclear Extended Range Aircraft) propulsion system. (Reference 6).

Table 3-1 summarizes the reference requirements utilized in this study.

TABLE 3-1

REFERENCE PROPULSION SYSTEM REQUIREMENTS

NUCLEAR CRUISE ALTITUDE	30,000 ft (Standard Day)
MACH NUMBER	0.75
CRUISE NET THRUST PER ENGINE	18,000 lbs
NUMBER OF ENGINES	4
REACTOR LIFETIME	10,000 Effective Full Power Hours
DOSE RATE - DURING OPERATION	5 mr/hr (20 Ft Forward and and Aft of Reactor Centerline)
- 30 MINUTES AFTER SHUTDOWN	5 mr/hr (20 Ft in All Directions from Reactor Centerline)
CONTAINMENT DESIGN IMPACT VELOCITY	250 ft/sec
LENGTH OF SECONDARY PIPING REQUIRED	606 ft (Total)

4.0 BI-BRAYTON STUDIES

This section presents the results of analyses of a Bi-Brayton cycle coupled to a gas cooled reactor and evaluation of secondary loop working fluids. The studies were conducted for the same base case application that was used for the cycle comparisons in the Innovative Aircraft Desigh Study, Task II (Reference I).

4.1 GENERAL

Several nuclear propulsion cycle concepts were investigated in the Innovative Aircraft Design Study Task II (IADS) to identify the minimum weight propulsion system. The investigations of that study showed that the nonrecuperated closed Brayton cycle with a dual-mode engine was potentially attractive due to several characteristics of such a system. Among these are:

- Lighter in weight than the other cycles.
- All of the piping in the wings is at relative low temperature.
- The piping in the wings contains only inert gas rather than liquid metal.
- In the dual-mode closed Brayton system, the chemically-fueled engines operate only on chemical fuel. Therefore, the engines can be optimized for the turbine inlet temperatures achievable with chemical fuel without having to be degraded to also allow operation at the lower turbine inlet temperature associated with nuclear operation.
- The closed Brayton power conversion system is compatible with a direct cycle gas cooled reactor.

The weight comparison of the base open Brayton and the closed Brayton powerplants from the Reference 1 IADS is shown in Table 4-1.

TABLE 4-1

INNOVATIVE AIRCRAFT DESIGN STUDY TASK II

BRAYTON CYCLE WEIGHT COMPARISONS (10^3 LB)

	BASE CASE OPEN BRAYTON (DUAL MODE)	RECUP. CLOSED BRAYTON (DEDICATED)	NONRECUP. CLOSED BRAYTON (DEDICATED)	NONRECUP. CLOSED BRAYTON (DUAL MODE)
NSS	462	477	499	460
ENGINE HX	77	3	3	3
PRECOOLER/CONDENSER	-	22	24	20
RECUPERATOR	-	22	2	-
PIPING	36	39	16	15
AUXILIARIES	21	25	25	21
CHEM. ENGINES	-	99	99	-
FANS, GEARS, STRUCT.	-	35	29	-
TURBS. AND COMPS.	-	13	28	17
ENGINES w/o HX	109	-	-	116
NACELLE PENALTY	-	6	6	5
TOTAL	705	741	731	657

A variation of the closed Brayton cycle, called the Bi-Brayton cycle, had been identified by earlier Westinghouse studies for other applications and a patent applied for. As the Reference I IADS and Reference 2 study results were obtained, it became apparent that the Bi-Brayton system concept also has application to the nuclear aircraft propulsion application. The Bi-Brayton system retains the desirable characteristics of the closed Brayton system while also permitting of a gas cooled reactor to the power transmission and conversion system in a manner such as to fulfill the safety criteria while eliminating the need for a high temperature intermediate heat exchanger. Furthermore, the intermediate heat exchanger size is reduced because only about three-fourths of the reactor energy is transmitted across the heat exchanger. Of particular importance in maximizing system reliability is the fact that the Bi-Brayton intermediate heat exchanger is exposed to temperatures $700^{o}F$ lower than the reactor outlet temperature.

In the Bi-Brayton concept of Figure 4-1, the high temperature turbine (located in the primary system) extracts the work necessary to drive both the primary and the secondary system compressors. The energy contained in the relatively lower temperature gas exiting from the primary system turbine is transferred through the intermediate heat exchanger to the secondary system to provide additional power to drive the power turbine. After the primary system gas is cooled and exits from the heat exchanger, it is directed to the primary system compressor where it is recompressed by an amount equal to the primary system pressure losses and turbine pressure ratio. Powering of the secondary system compressor by the primary turbine maximizes the portion of the total system temperature drop that is taken in the primary loop turbine and therefore minimizes the peak temperatures in the intermediate heat exchanger.

The secondary system power turbines are located remotely in the nacelles driving ducted fans (the fans can alternatively be driven by a JP fueled engine for nonnuclear operations). The energy rejected through the precooler is added to the fan discharge air flow for a thrust benefit. Because the fluid of the secondary system is physically separated from the primary system fluid, reasonable freedom exists in selection of the secondary fluid. In addition, the secondary fluid can be maintained at pressure level close to that of the primary to minimize the pressure drop during normal operation across the tubes of the intermediate heat exchanger.

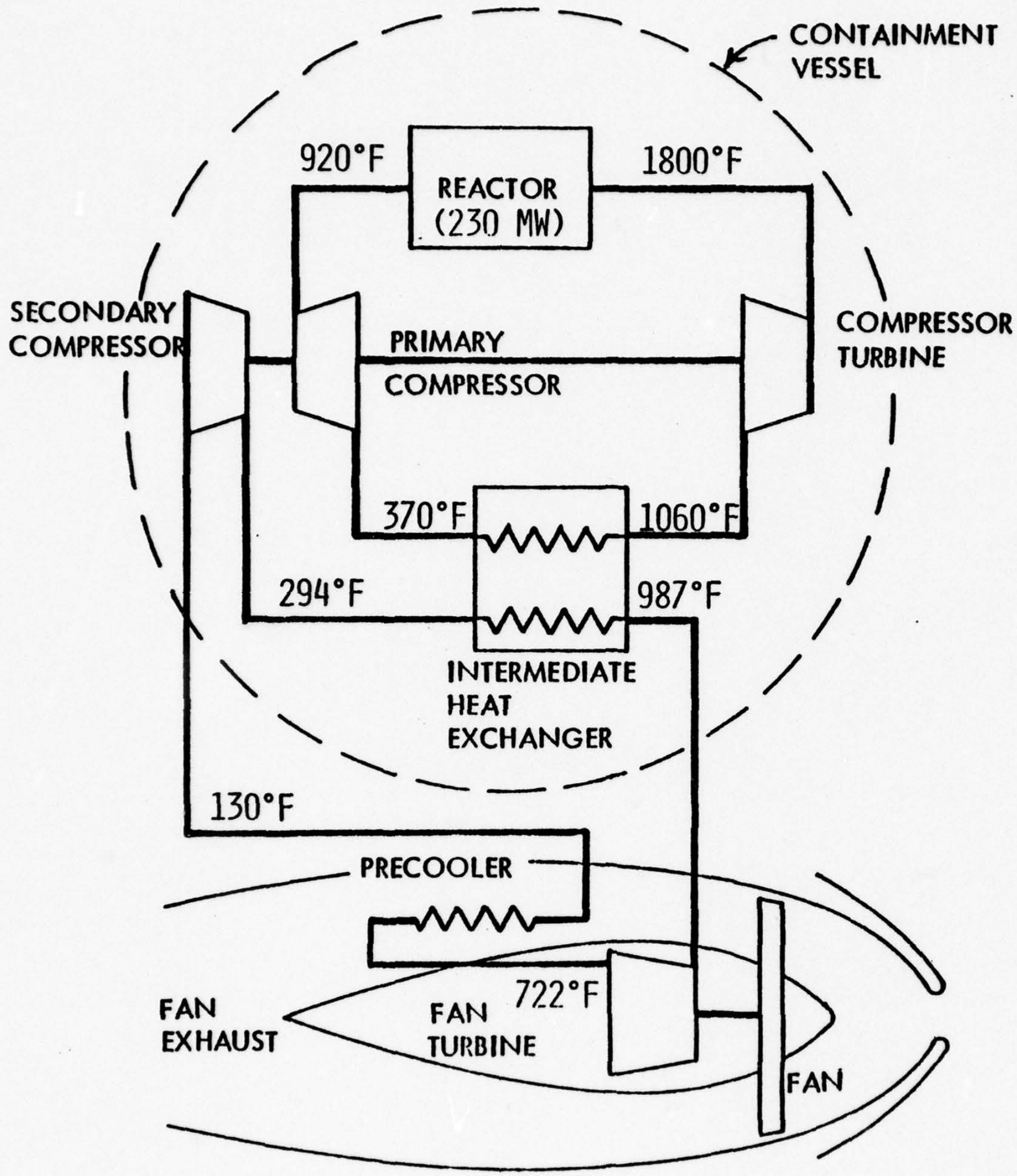

Figure 4-1. Bi-Brayton System Schematic

Previous studies performed by Westinghouse indicated that such a system is competitive on a weight basis with current concepts and should have attractive powerplant-to-aircraft interface characteristics. This study was performed to evaluate the Bi-Brayton system of Figure 4-1 and to define its characteristics in response to specific USAF requirements.

4.2 BI-BRAYTON CYCLE STUDIES

The reference data used for these Bi-Brayton cycle analyses are shown in Table 4-2. For simplicity in comparing variants of the basic Bi-Brayton cycle, no bleed flows for turbine cooling were included. This assumption produces slightly higher cycle efficiencies but has a negligible effect on the comparisons. In the Reference 7 study, it was found that equal flow rates in the primary and secondary systems resulted in the highest cycle efficiencies. Therefore, equal primary and secondary flow rates were used in these cycle studies. In this study, the pressure loss in the heat exchangers is calculated and therefore increases as heat exchanger effectiveness increases. This assumption is judged to be more realistic than the usual assumption of fixed cycle pressure losses, independent of heat exchanger effectiveness.

As in most Brayton cycles, the turbine and compressor pressure ratios effect cycle efficiency, this effect for the base Bi-Brayton system is shown in Figure 4-2. This plot shows that the minimum reactor power of 227 MWt occurs at about a primary turbine pressure ratio of 3.0 and that at pressure ratios between 2.5 and 4.0 there is only a small effect on reactor power.

TABLE 4-2

BI-BRAYTON

REFERENCE DATA FOR CYCLE COMPARISONS

Altitude	30,000 ft
Mach Number	0.75 Standard Day
Dual Mode Engines:	
• Number of Engines	4
• Cruise Thrust per Engine (net)	18,000 lb
Fan Efficiency	93%
Turbine Efficiency	93%
Compressor Efficiency	90%
LWNP is the Reference Nuclear System	
Helium Properties	Reference 10
Effective Full Power Hours	10,000

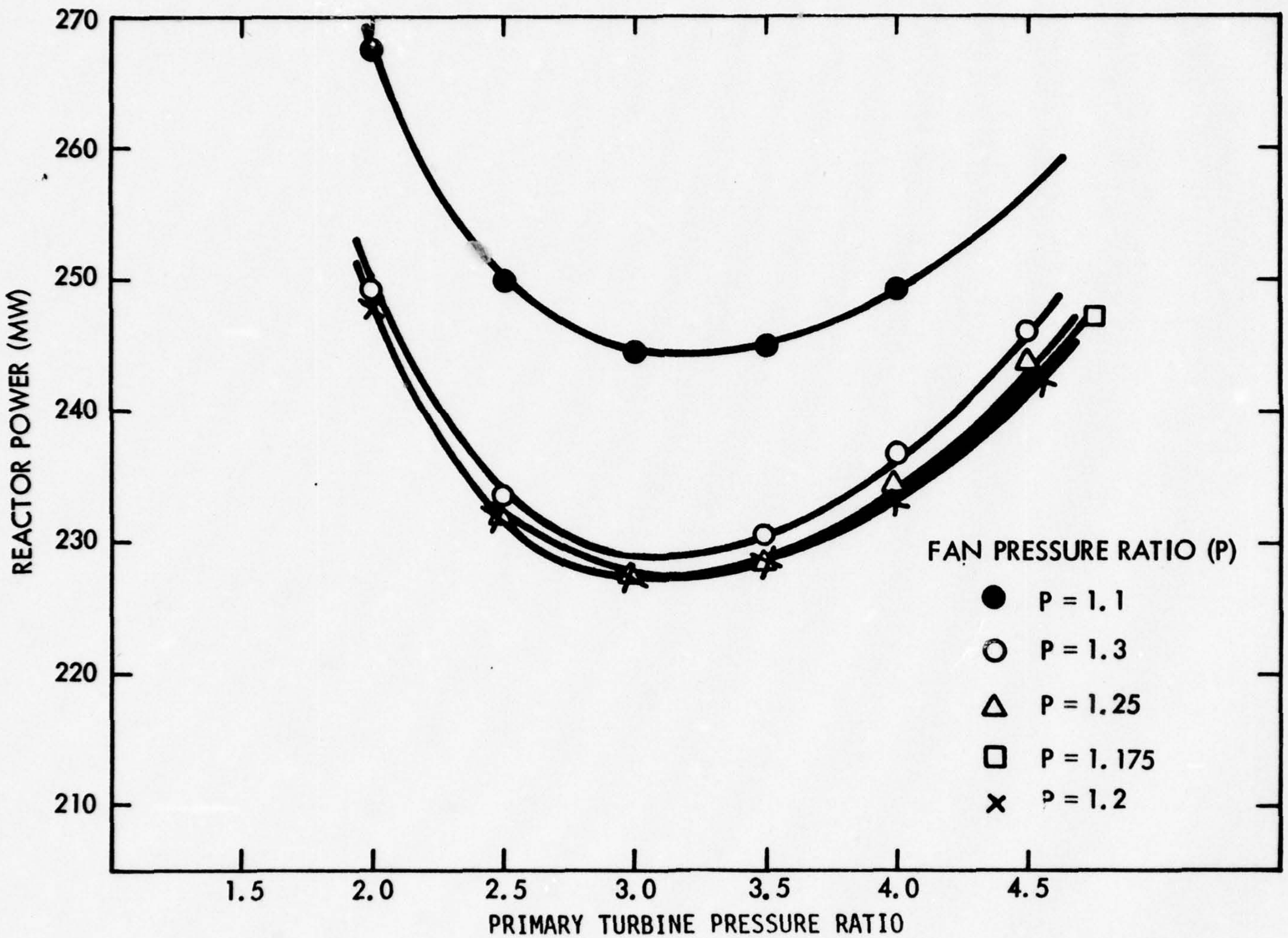

Figure 4-2. Reactor Power Versus Turbine Pressure Ratio (Base Case)

The reactor thermal power to produce the required thrust of 72,000 pounds is shown in Figure 4-3 as a function of fan pressure ratio for several primary turbine pressure ratios. Propulsion efficiency increases as the fan pressure ratio increases up to the point where the fan nozzle velocity becomes sonic. However, as the fan pressure ratio is increased, the fan exit air temperature (which is the sink temperature for the closed Bi-Brayton cycle) increases, which reduces cycle efficiency. The net result is that the reactor power is relatively insensitive to fan pressure ratios above 1.15. This relatively large fan pressure ratio range is attractive, so that a fan pressure ratio could be selected based on take-off and climb performance under fossil fuel power and still produce good performance under nuclear power. Figures 4-4 and 4-5 show the variation in reactor power for imtermediate heat exchanger effectiveness of 0.85 and 0.95. In both figures, the reactor power with an intermediate heat exchanger effectiveness of 0.90 is shown for comparative purposes. As can be seen, a heat exchanger effectiveness of 0.90 results in the lowest reactor power. As the effectiveness decreased, the temperature entering the primary compressor increased, causing a rise in pumping power and necessitating a rise in reactor power. Increasing the effectiveness reduced the pumping power by lowering the inlet temperature, but raised the flow pressure drop due to the larger heat exchanger unit that was needed. Beyond a certain point, the additional energy transferred with a larger effectiveness was not sufficient to overcome the additional pumping power necessary. This was why the reactor power was greater at an effectiveness of 0.95 than the base case value of 0.90.

In weight considerations, the intermediate heat exchangers do not effect the containment diameter as long as the effectiveness is less than about 0.9. However, in increasing the effectiveness to 0.95 the heat exchanger length is about doubled and would significantly increase both containment weight and diameter.

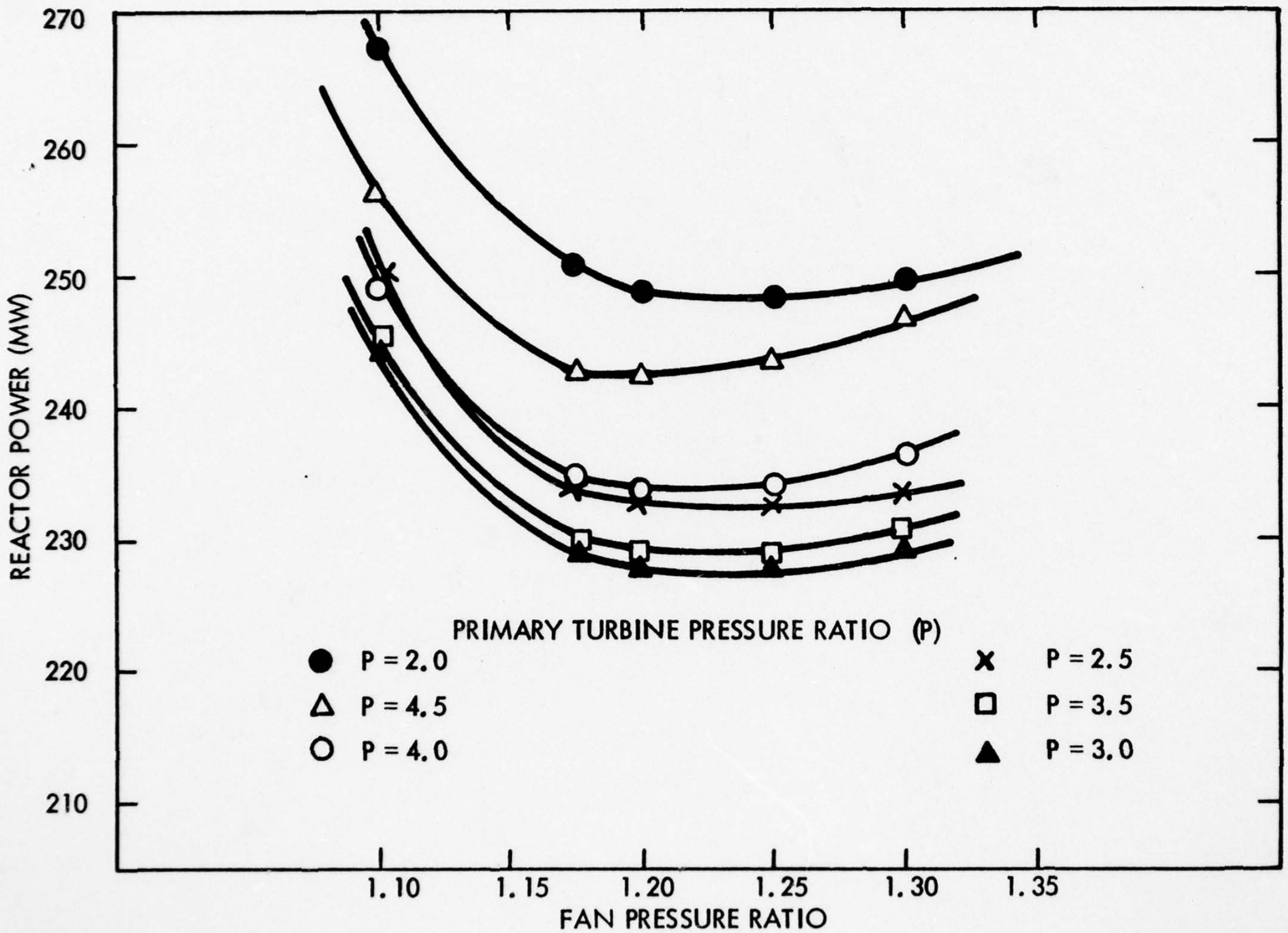

Figure 4-3. Reactor Power Versus Fan Pressure Ratio (Base Case)

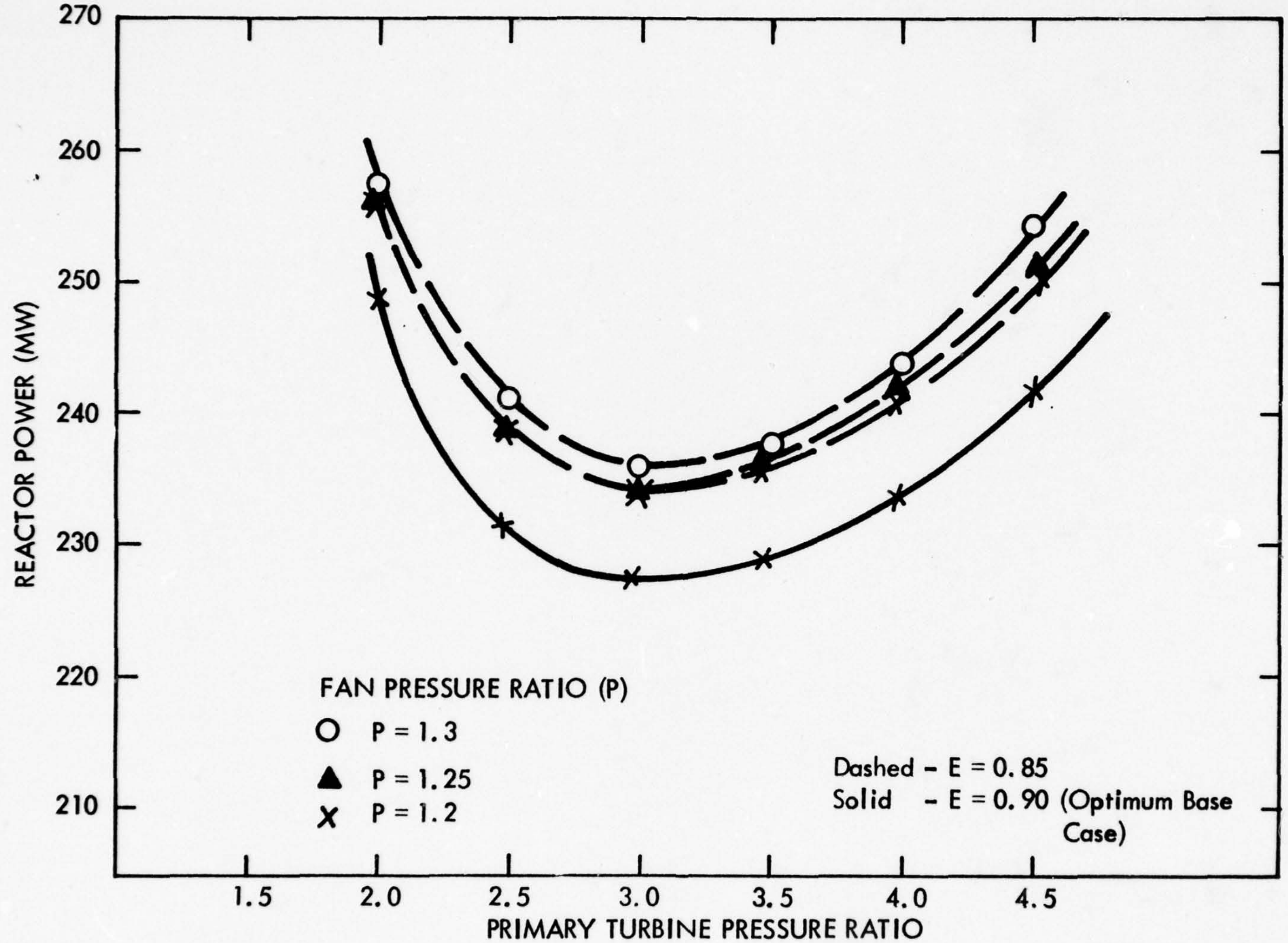

Figure 4-4. Reactor Power Versus Turbine Pressure Ratio (Heat Exchanger Effectiveness (E) = 0.85)

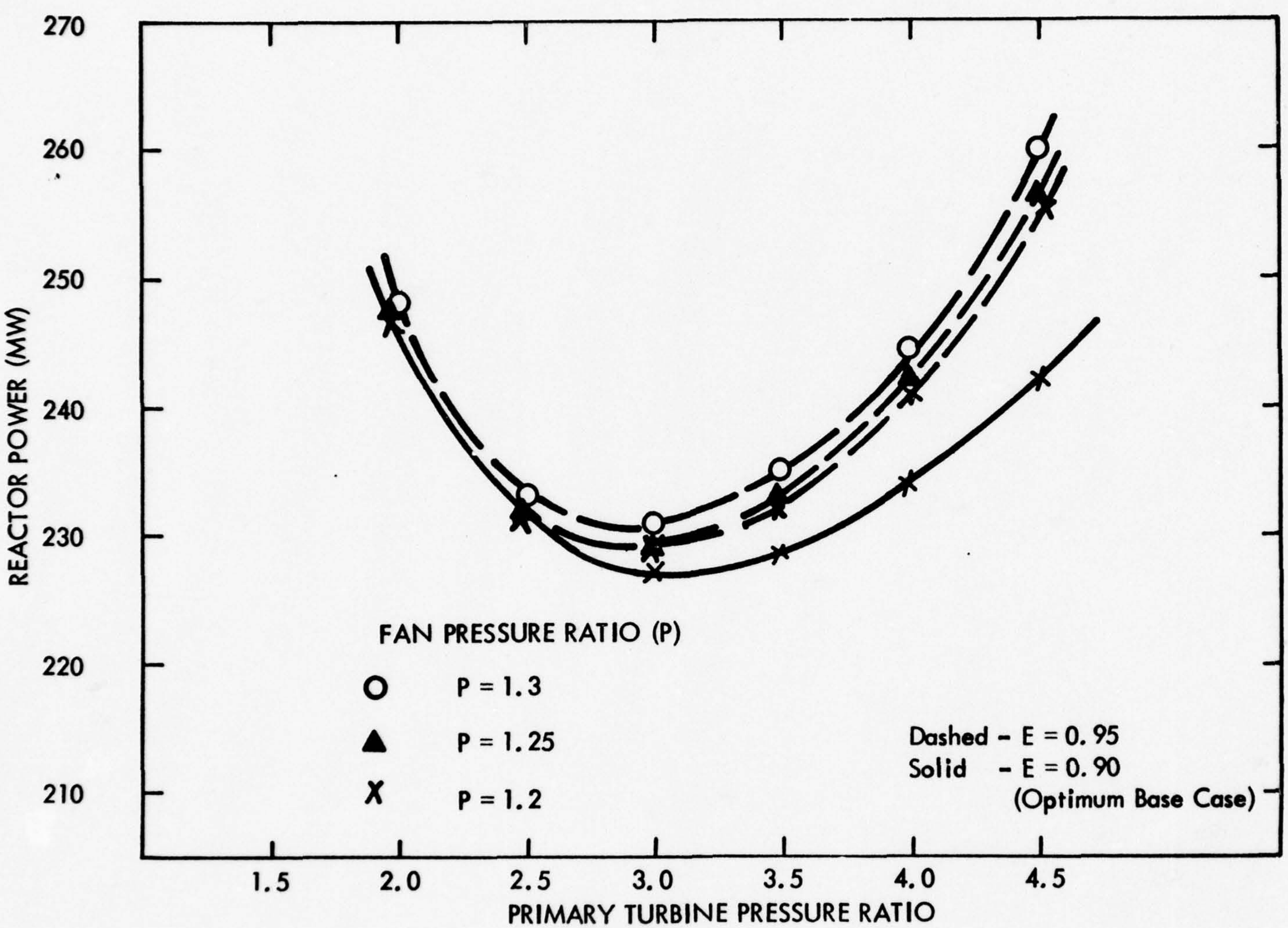

Figure 4-5. Reactor Power Versus Turbine Pressure Ratio (Heat Exchanger Effectiveness (E) = 0.95)

In the Compact Closed Cycle Brayton System Feasibility Study (Reference 7), it was found that adding heat exchangers in the Bi-Brayton system to further cool the working fluids before compressing resulted in the lowest system weight for that application. Therefore, in this Bi-Brayton cycle study, two modifications to the base Bi-Brayton system of Figure 4-1 were also investigated.

The first modification to the basic Bi-Brayton cycle is schematically shown in Figure 4-6; in this case the secondary working fluid is further cooled in a ducted cooler (reject heat exchanger) after being cooled in the precoolers and before entering the secondary compressors. This both reduces the work of the secondary compressor and lowers the secondary compressor fluid exit temperature; which in turn lowers the primary fluid exit temperature from the intermediate heat exchanger reducing the primary compressor work. This results in reducing the reactor power approximately 17 MW (about 8 percent) as shown in Figure 4-7. The 8 percent reduction in reactor power produces about 3 percent reduction (~11,000 lbs) in nuclear subsystem weight. However, the weight of ducted coolers needed to accomplish this reduction in reactor power would more than offset the savings in reactor weight. The size of the ducted coolers (assuming two coolers) are 13.6 feet in diameter by 34 feet long. Therefore, for this application, this first modification of Bi-Brayton system is not attractive.

The second modification to the basic Bi-Brayton cycle is shown schematically in Figure 4-8. In this modification the primary fluid is further cooled in heat exchangers placed between the intermediate heat exchangers and the primary compressors. The energy absorbed in this heat exchanger is transported via a closed liquid loop to the fan air. The reactor power versus primary turbine pressure ratio is shown in Figure 4-9 for this second modification. There is about a 14 percent reduction in reactor power compared to the base Bi-Brayton cycle which results in about 5 percent (18,000 lbs) reduction in reactor and shield weight. The primary turbine pressure ratio must be increased from 3.0 for the base case to about 4.5 which results in more stages in both

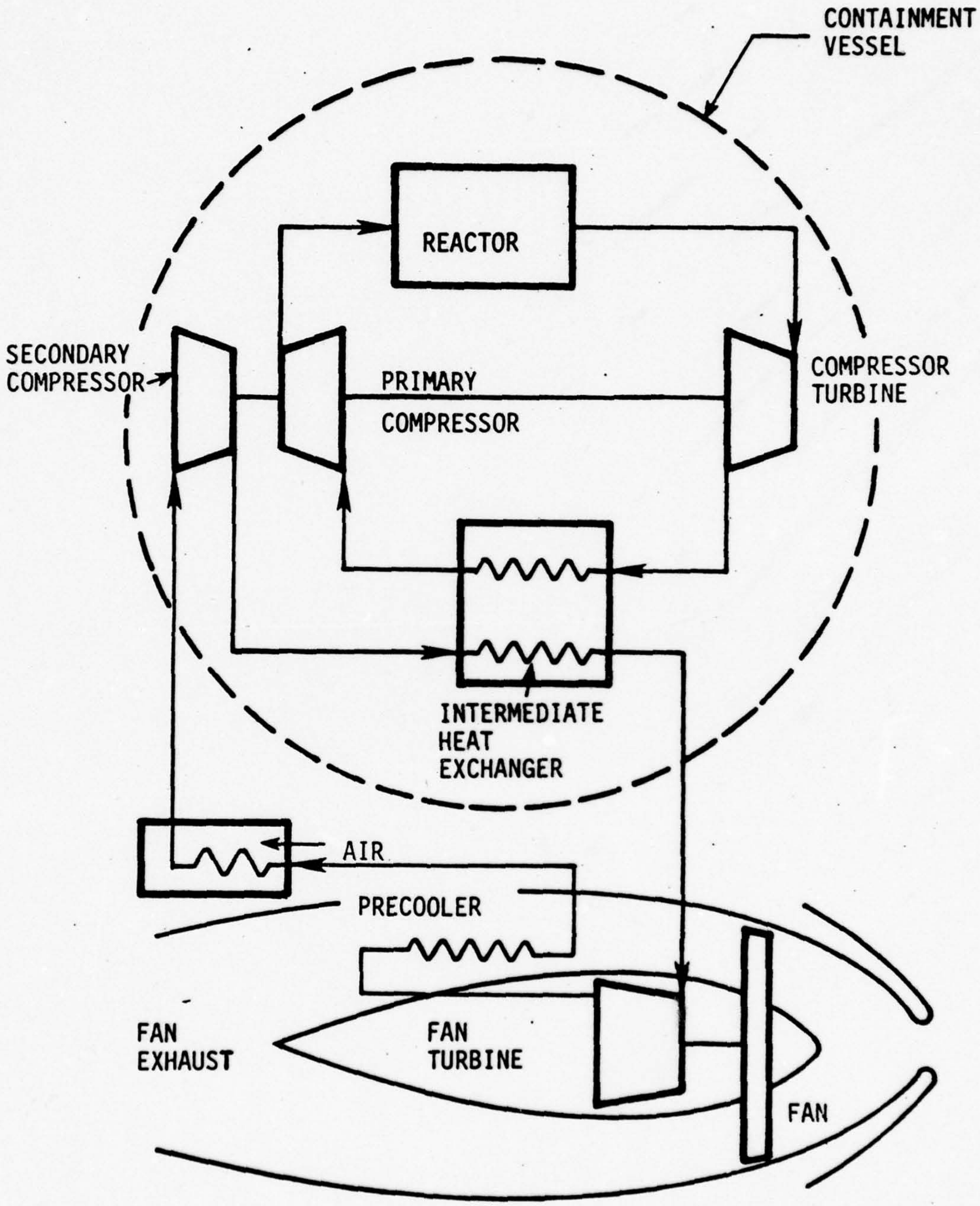

Figure 4-6. Bi-Brayton System with Secondary Side Reject Heat Exchanger

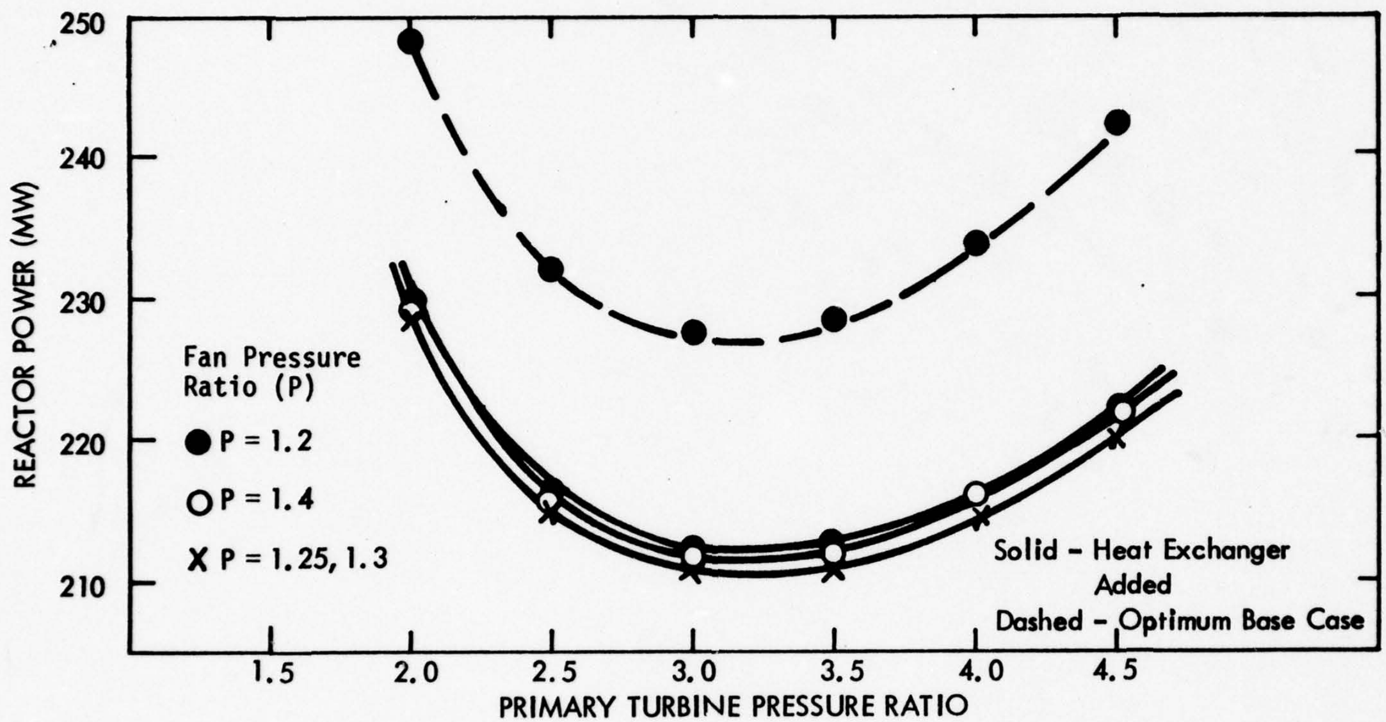

Figure 4-7. Reactor Power Versus Turbine Pressure Ratio
(Heat Exchanger in Secondary Line)

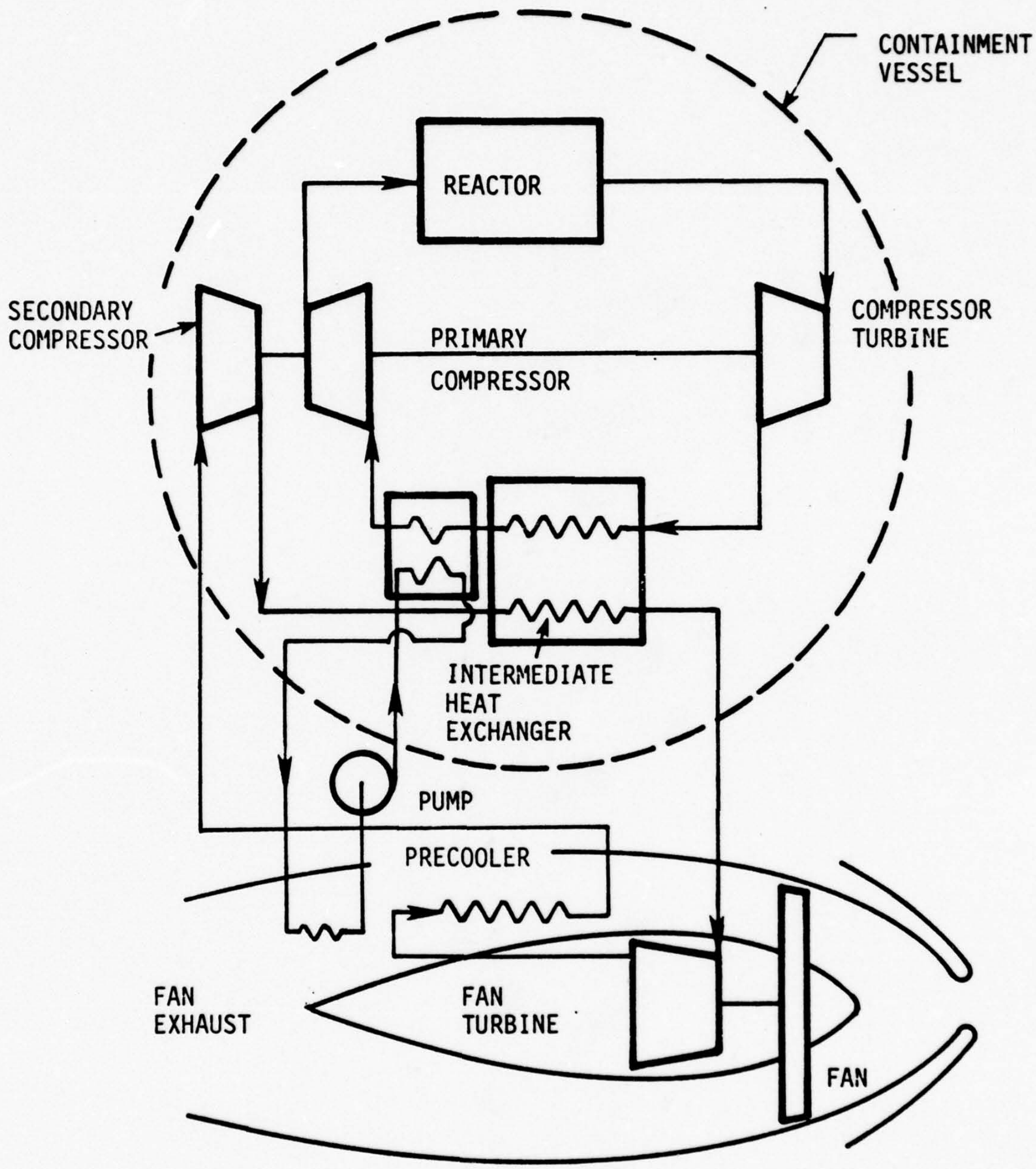

Figure 4-8. Bi-Brayton System with Primary Side Heat Exchanger (Heat Goes to Fan Air)

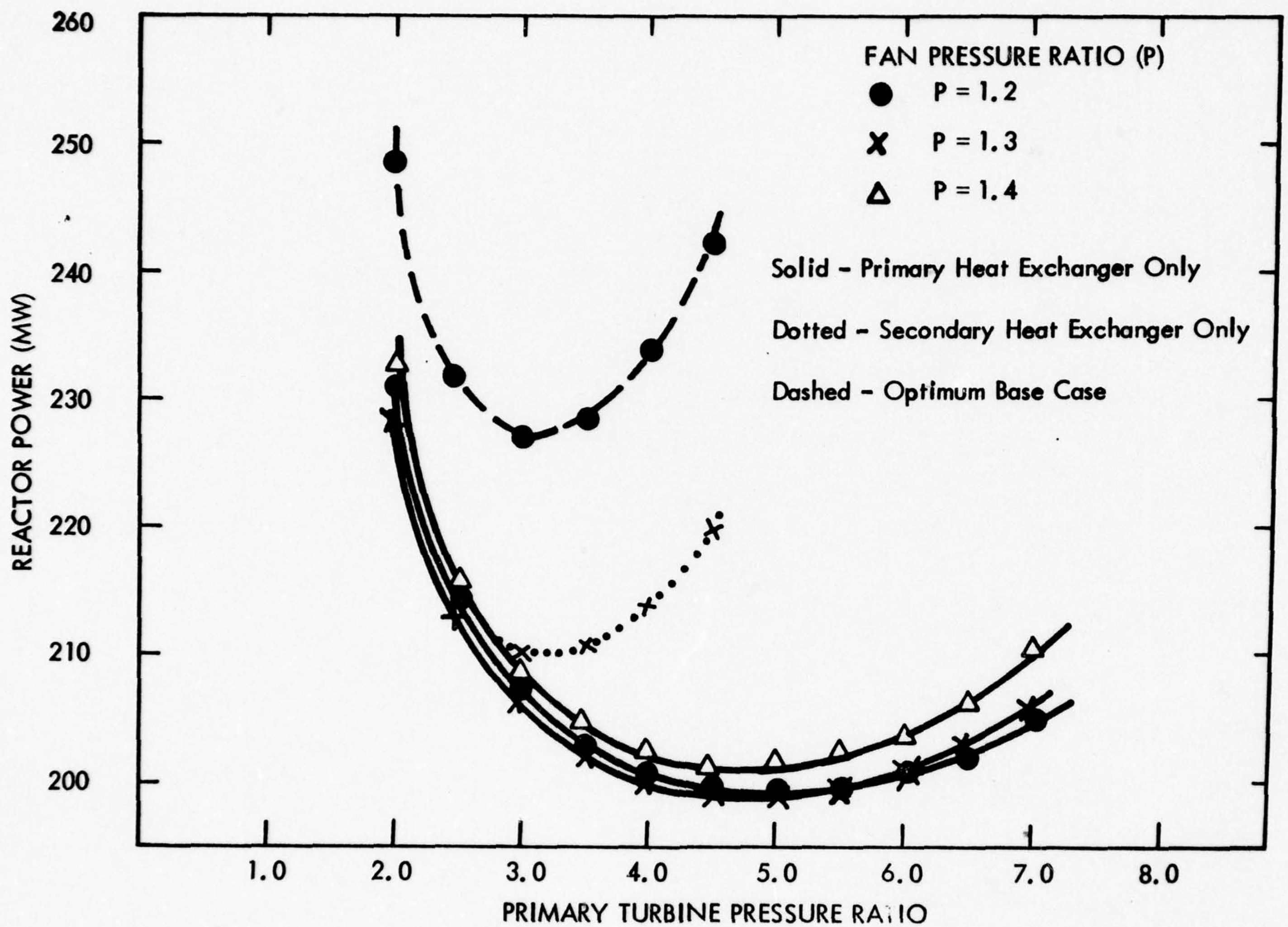

Figure 4-9. Reactor Power Versus Turbine Pressure Ratio
(Heat Exchanger in Primary Line - Heat Goes to Fan Air)

turbines and compressors and increases the length of the turbo-compressor units. Additional heat exchangers are required in an already crowded containment vessel. The above two items increase the containment diameter and weight (13,500 lbs). Also, the additional equipment external to the containment (pumps, piping and heat exchangers in the engines) result in about a washout in total powerplant weight. This second modification, with its added complexity and no significant weight savings, does not appear attractive for this application.

4.3 SECONDARY LOOP WORKING FLUID ANALYSIS

The fluid in the secondary system of the Bi-Brayton cycle is physically separated from the primary system fluid and reasonable freedom exists in the selection of the secondary fluid. A higher molecular weight gas could reduce the number of stages in both the secondary compressors and the power turbines. Air may be a desirable secondary fluid due to its availability. The effects of air, pure gases and gas mixtures on heat exchanger size (weight), piping size and turbomachinery were investigated.

4.3.1 Gas Property Effects on Heat Exchanger Characteristics

Considering a single coolant channel with axial turbulent flow, correlations may be applied to any flow cross section that can be described adequately by a hydraulic diameter (D)

$$D = \frac{4\ A\ L}{S} \tag{1}$$

The heat transfer area (S)

$$S = \frac{Q}{h\Delta T} \tag{2}$$

and the pressure drop (ΔP)

$$\Delta P = f\,\frac{L}{D}\,\frac{v}{2\,g}\left(\frac{W}{A}\right)^2 \tag{3}$$

For air and helium, the heat transfer coefficient (h) may be expressed by Dittus Boelter equation

$$h = 0.021\,\frac{k}{D}\left(\frac{WD}{A\mu}\right)^{0.8} Pr^{0.4} \tag{4}$$

The specific volume (v) is calculated from the perfect gas equation of state

$$v = \frac{RT}{MP} \tag{5}$$

The thermal power (Q) transferred is

$$Q = W\,C_p\,\delta T \tag{6}$$

For turbulent flow, the friction factor (f) may be approximated by (R_e from 5000 to 200,000)

$$f = \frac{0.184}{\left(\frac{WD}{A\mu}\right)^{0.2}} \tag{7}$$

The specific heat per mol (K_p)

$$K_p = C_p M \tag{8}$$

The three characteristic dimensions of the coolant channel (flow cross section area A, length L, and heat transfer surface area S) are obtained from equations (1) to (8):

$$A = (P_r)^{0.3}\ \frac{\sqrt{M}}{K_p} \left[\frac{RT}{P}\ \frac{0.034}{\delta T\ \Delta T\ \Delta P}\right]^{1/2} Q \tag{9}$$

$$L = \frac{(P_r)^{0.54}\ (M)^{0.1}}{\mu^{0.2}} \left[\frac{P}{RT}\right]^{0.1} \left[\frac{\delta T}{\Delta T}\right]^{0.9} \frac{\Delta P^{0.1} D^{1.2}}{0.0599} \tag{10}$$

$$S = \frac{(P_r)^{0.84}\ (M)^{0.6}}{\mu^{0.2}\ K_p} \left[\frac{RT}{P}\right]^{0.4} \frac{\delta T^{0.4}}{\Delta T^{1.4}}\ \frac{Q\ D^{0.2}}{\Delta P^{0.4}\, 0.0812} \tag{11}$$

The effect of fluid properties (P_r, M, K_p and μ) on flow area, length and surface area according to equations (9) to (11) is shown on Figure 4-10. Helium is used as the reference, because it is best in regard to all three characteristic dimensions. To minimize volume (~AL), it is desirable for the gas to have low molecular weight, low Prandtl Number, and high molar specific heat.

The fluid state (P/RT) has a weak influence on length, while both flow area and heat transfer area are influenced by temperature and pressure level. The thermal

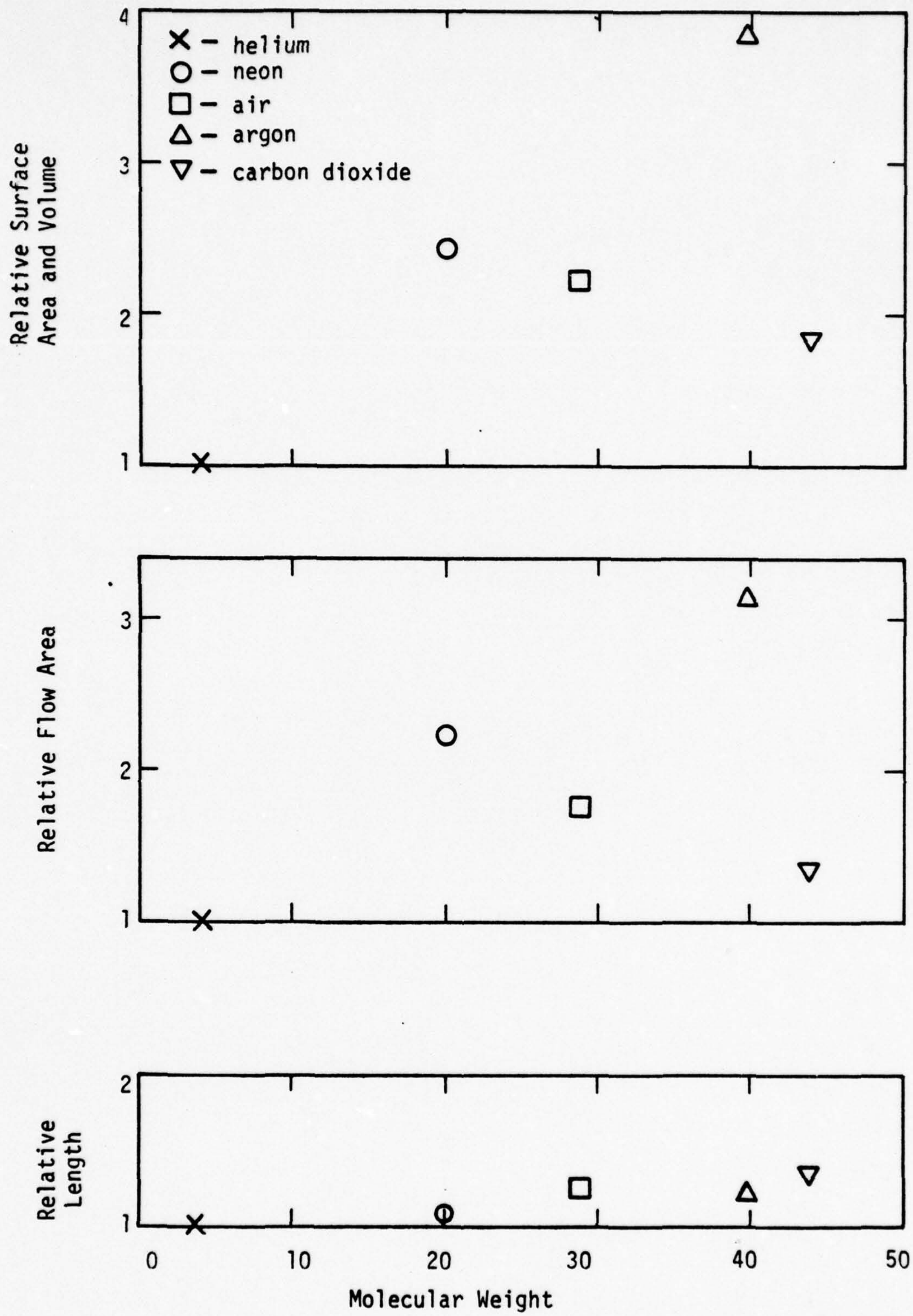

Figure 4-10. Effect of Fluid Properties of Pure Gases and Air on Heat Exchanger Dimensions (Fluid Properties Evaluated at 800 K from References 3, 4, and 5)

power level does not effect length, while both surface and flow areas are proportional to it. The gas temperature difference (δT qual to absolute difference between inlet and outlet temperature) is almost proportional to length, while flow area decreases and surface area increases with increasing δT. An increase in the temperature difference ΔT between the channel surface and gas gives a very significant reduction in surface area, a strong reduction in length and a slight reduction in flow area. An increase in pressure drop produces a reduction in flow and surface area and a very slight increase in length. The effect of hydraulic diameter is significant on length, is weak on surface area and does not appear in the flow area equation (9).

Reference 8 and 9 reported the results of research conducted for the Office of Naval Research. Reference 8 indicated that the Prandtl Number dependence in equation (4) is not adequate for low Prandtl Number mixtures of noble gases. The results of experimental investigations of heat transfer (Reference 9) for turbulent flow of helium-argon mixtures confirmed that prediction. An equation of similar form to equation (4), but with the exponent of the Prandtl Number changed to 0.55 is recommended (Reference 9).

$$h = 0.021\,\frac{k}{D}\left(\frac{WD}{A\mu}\right)^{0.8}\left(P_r\right)^{0.55} \tag{12}$$

Using equation (12) in place of equation (4), the three characteristic dimensions of the coolant channel for mixtures of gases are:

$$A = \frac{(P_r)^{0.225}\sqrt{M}}{K_p}\left[\frac{RT}{P}\cdot\frac{0.034}{\delta T\ \Delta T\ \Delta P}\right]^{1/2} Q \tag{13}$$

$$L = \frac{(P_r)^{0.405}\,M^{0.1}}{\mu^{0.2}}\left[\frac{P}{RT}\right]^{0.1}\left[\frac{\delta T}{\Delta T}\right]^{0.9}\frac{\Delta P^{0.1}\,D^{1.2}}{0.0599} \tag{14}$$

$$S = \frac{(P_r)^{0.63}\,M^{0.6}}{\mu^{0.2}\,K_p}\left[\frac{RT}{P}\right]^{0.4}\frac{\delta T^{0.4}\,Q\,D^{0.2}}{\Delta T^{1.4}\,\Delta P^{0.4}\,0.0812} \tag{15}$$

Since the Prandtl Numbers for the gas mixtures are less than one, equations (13) to (15) predict larger characteristic dimensions than equations (9) to (11). the ratio of the characteristic dimensions for the two sets of equations are shown in Figure 4-11 as a function of Prandtl Number.

In the Bi-Brayton cycle, two types of heat exchangers must be considered (intermediate and reject). In the intermediate heat exchanger, helium will be used as the primary fluid (tube side); however, the secondary system (shell side) is not restricted to the use of helium. Binary mixtures of helium and heavier molecular weight gases and other gases can be considered as possible secondary working fluids. The increase in density, due to increased molecular weight, may reduce the size of the turbines and compressors; however, this may cause an increase in the size of the heat exchangers.

In minimizing the total cross-sectional area of the intermediate heat exchanger, the subdivision of the pumping power and the temperature difference available must be considered. The efficiency of the Bi-Brayton cycle depends on the sum of the pressure drops on both sides of the heat exchanger. Therefore the boundary conditions are:

$$\Delta P = \Delta P_t + \Delta P_s = \text{constant} \qquad (16)$$

$$\Delta T = \Delta T_t + \Delta T_s = \text{constant} \qquad (17)$$

For the intermediate heat exchanger, several assumptions are used:

Equal flow stream capacity rates

$$W_t C_{pt} = W_s C_{ps} \qquad (18)$$

Therefore

$$\delta T_t = \delta T_s \qquad (19)$$

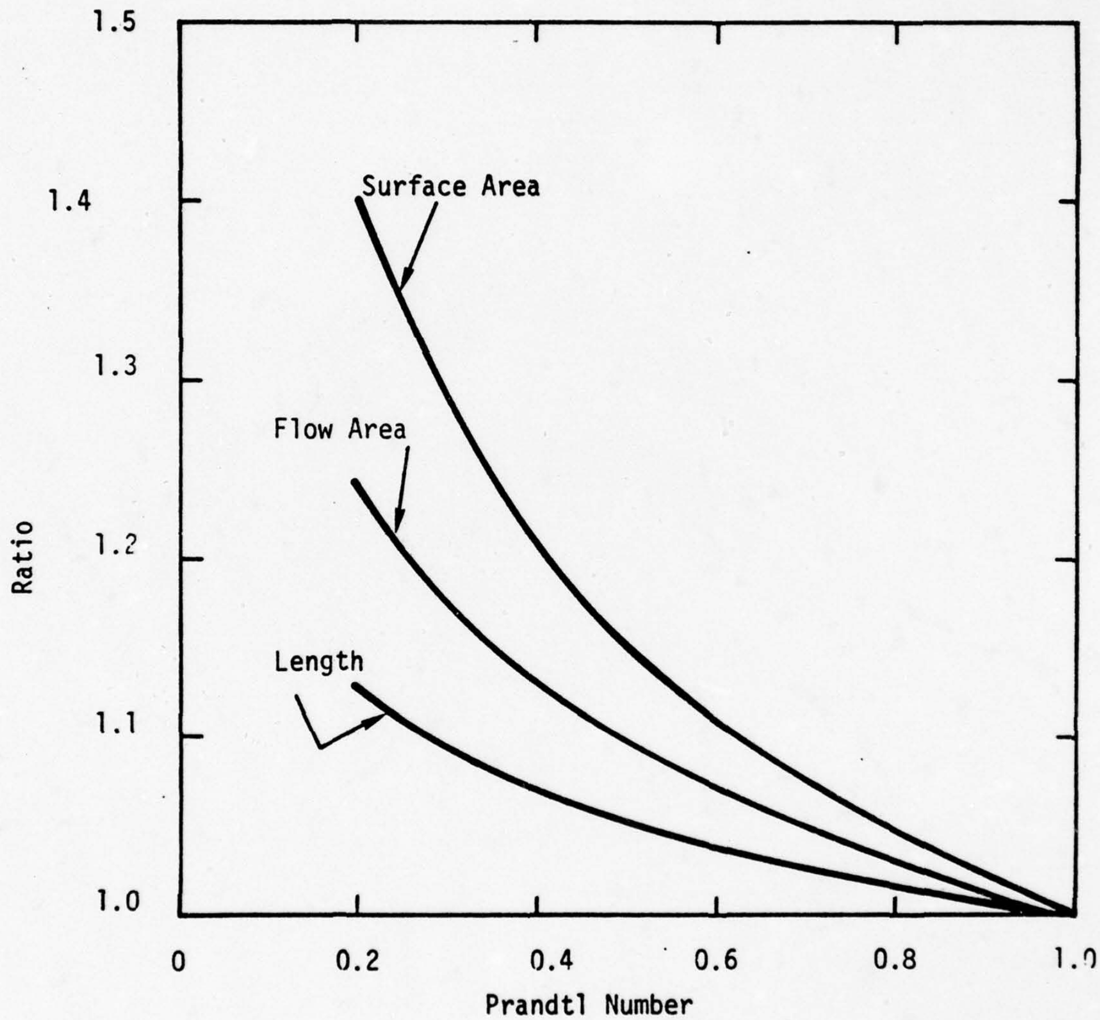

Figure 4-11. Ratio of Characteristic Dimensions of Heat Exchangers with Gas Mixtures to Pure Gases

For a tube and shell heat exchanger

$$S_t \frac{D_{so}}{D_t} = S_s \tag{20}$$

No thermal resistance in the tube wall and that

$$\frac{St_t}{(P_r)_t^{0.6}} D_t = \frac{St_s}{(P_r)_s^{0.45}} D_{so} \tag{21}$$

From

$$Q = h_t \, \Delta T_t S_t = h_s \, \Delta T_s S_s \tag{22}$$

and from (6) and (21)

$$\Delta T_t = \Delta T \, \frac{A_t}{A} \tag{23}$$

$$\Delta T_s = \Delta T \, \frac{A_s}{A} \tag{24}$$

From equation (9) for the tube side

$$A_t = \frac{(P_r)_t^{0.3} \sqrt{M_t}}{K_{pt}} \left[\frac{RT_t}{P_t} \quad \frac{0.034}{\partial_t \, \Delta T \, \frac{A_t}{A} \, \Delta P} \right]^{1/2} Q$$

or

$$A_t = \left[\frac{A}{\Delta T}\right]^{1/3} \left[\frac{(P_r)_t^{0.3}}{K_{pt}} \, Q \left\{ \frac{M_t RT_t 0.034}{P_t \, \delta T} \right\}^{1/3} \right]^{2/3} \frac{1}{\Delta P_t^{1/3}}$$

From equation (13) for the shell side

$$A_s = \left[\frac{A}{\Delta T}\right]^{1/3} \left[\frac{(P_r)_s^{0.225}}{K_{ps}} \; Q \left\{\frac{M_s R T_s 0.034}{P_s \quad \delta t}\right\}^{1/2}\right]^{2/3} \frac{1}{\Delta P^{\,1/3}}$$

Since

$$A = A_t + A_s$$

$$A = \frac{Q}{\Delta T^{1/2}} \quad \frac{(P_t)^{0.3}}{K_{pt}} \left[\left[\left\{\frac{M_t R T_t 0.034}{P_t \quad \delta t}\right\}^{1/2} \frac{1}{\Delta Pt^{1/2}}\right]^{2/3}\right.$$

$$\left. + \left[\frac{(P_t)_s^{0.225}}{K} \left\{\frac{M_s R T_s 0.034}{P_s \;\delta t}\right\}^{1/2} \frac{1}{(\Delta P - \Delta P_t)^{1/2}}\right]^{2/3}\right]^{3/2}$$

From

$$\frac{dA}{d\;\Delta P_t} = 0$$

$$\left(\frac{\Delta P_t}{\Delta P_s}\right)_{opt} = \frac{(P_r)_t^{0.15} \; K_{ps}^{\;0.5}}{(P_r)_s^{0.1125} \; K_{pt}^{0.5}} \left[\frac{M_t T_t P_s}{M_s T_s P_t}\right]^{0.25} \tag{25}$$

The optimum pressure loss ratio for helium on the tube side and a mixture of helium and xenon on the shell side of the heat exchanger versus molecular weight is shown in Figure 4-12. For a tube and shell heat exchanger, the tube flow length equals the shell flow length. Therefore, using equations (10) and (14) an expression for the ratio of temperature differences is obtained.

$$\frac{\Delta T_t}{\Delta T_s} = \left[\frac{(P_t)_t^{0.54}}{(P_r)_s^{0.405}}\left(\frac{M_t}{M_s}\right)^{0.1}\left(\frac{M_s}{M_t}\right)^{0.2}\left(\frac{P_t T_s}{P_s T_c}\right)^{0.1}\left(\frac{\Delta P_t}{\Delta P_s}\right)^{0.1}\left(\frac{D_t}{D_s}\right)^{1.2}\right]^{1.11} \tag{26}$$

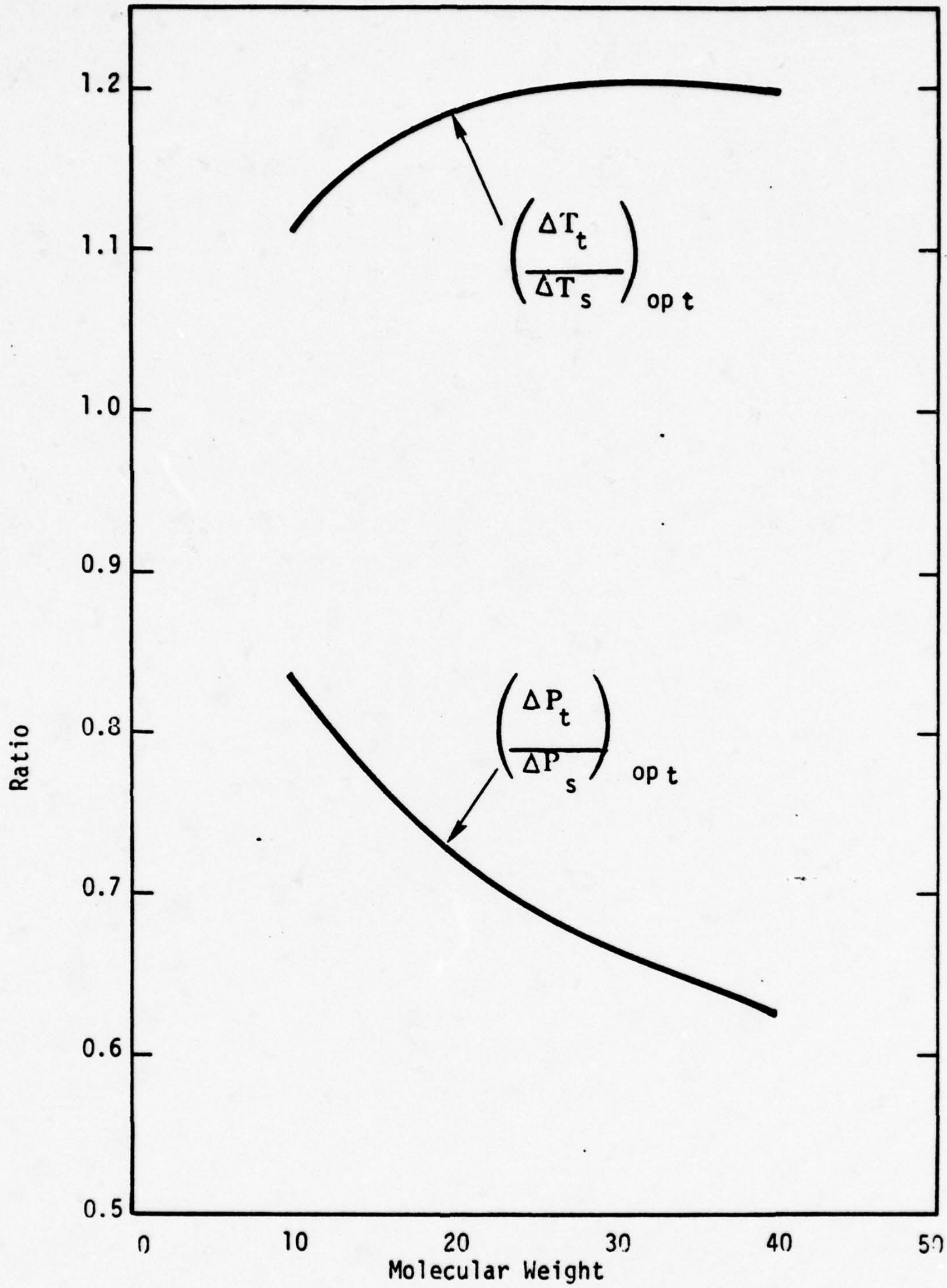

Figure 4-12. Optimum Tube to Shell Pressure Drop and Temperature Difference Ratios

(Helium on tube side and a mixture of helium and xenon on the shell side)

The above temperature difference ratio is also shown in Figure 4-12, with the assumption of equal shell and tube hydraulic diameters (D_t/D_s - 1) and using the pressure loss ratio from equation (25).

The relative heat exchanger volumes for pure gases, air, and binary mixtures are shown in Figure 4-13 with the same gas or gas mixture on both the tube and shell side. The gas mixtures (properties from References 10, 11 and 12) require less heat exchanger volume than the pure monatomic gases. In all cases except with the helium-xenon mixture, both the heat exchanger length and the flow area increase over that of a pure helium heat exchanger. In the case with helium-xenon mixture, the tube length is less than the tube length of a pure helium heat exchanger (~75 to 90 percent). Therefore, the heat exchangers for helium-xenon mixtures are short with large diameters in comparison with the pure helium heat exchanger shape. The helium-carbon dioxide mixture has the smallest increase in heat exchanger volume over that of a pure helium heat exchanger and the length to diameter ratio is about 0.95 in comparison to the pure helium heat exchanger.

Figure 4-14 shows the relative heat exchanger volumes of helium-xenon, helium-carbon dioxide mixtures and air on the shell side of the heat exchangers, with the helium on the tube side. Again, the helium-carbon dioxide mixture has the smallest increase in heat exchanger volume over that of a pure helium heat exchanger.

The use of any heavier molecular weight gas or gas mixture in place of helium in the secondary loops of the Bi-Brayton system requires increased intermediate heat exchanger volume and therefore increased weight (also increases containment weight and size.)

The reject heat exchanger runs at fan exit pressure (~10 psia) on the shell side and hence controls the overall thermal resistance. Therefore the required surface area (volume) of the reject heat exchanger will not vary significantly with the gas or gas mixture on the tube side.

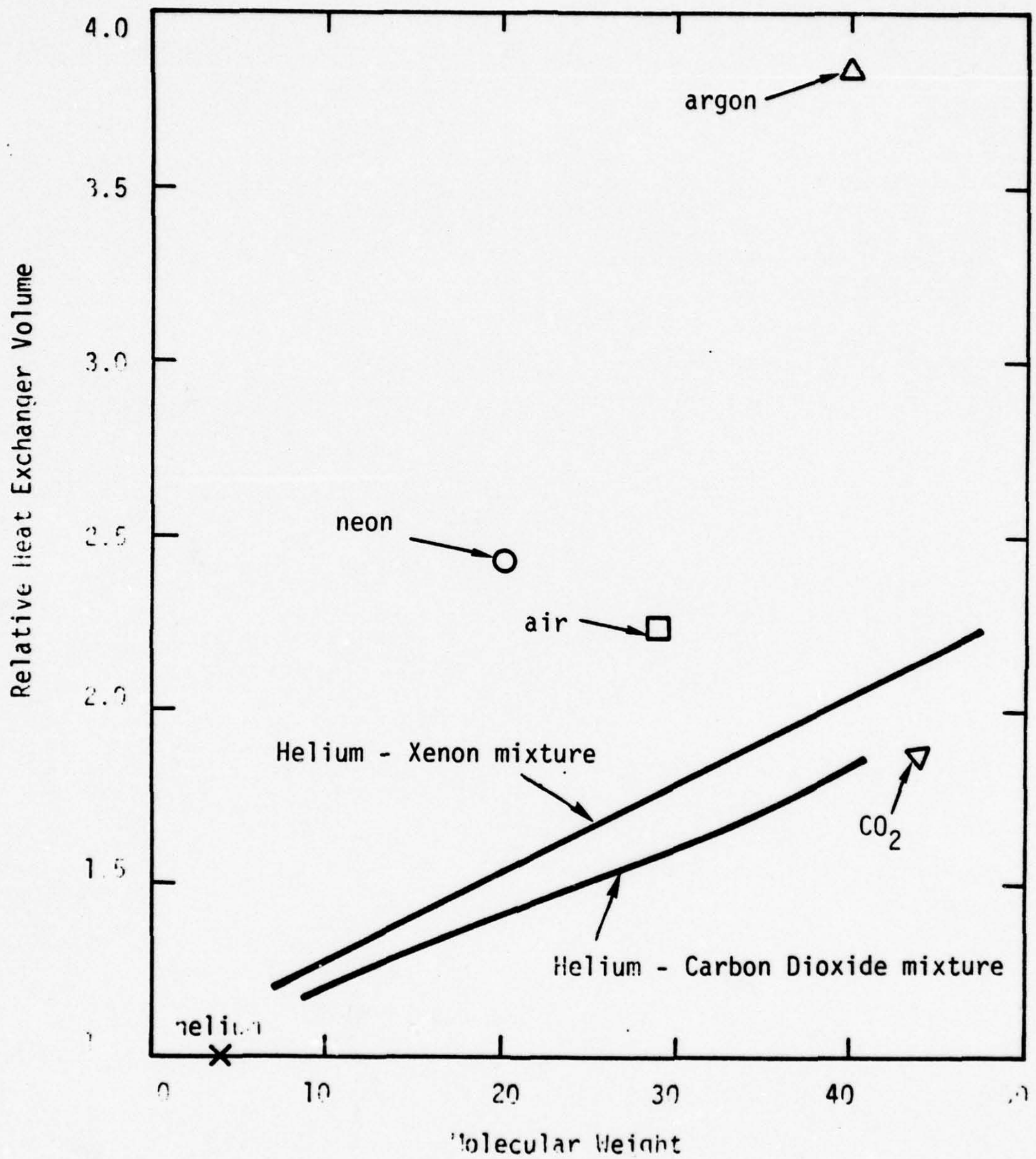

Figure 4-13. Relative Heat Exchanger Volume for Pure Gases, Air, and Binary Mixtures
(Same gas on both tube and shell side)

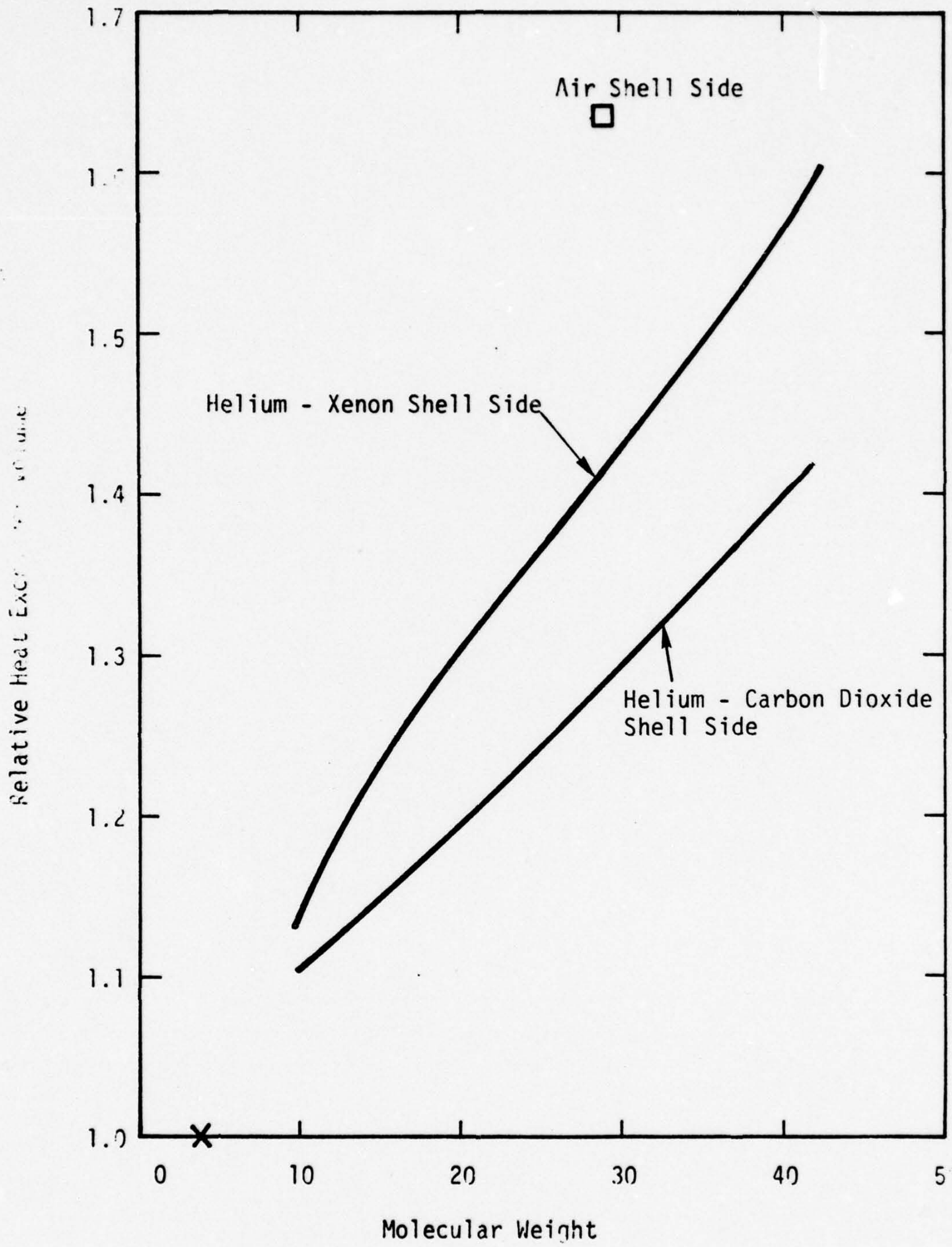

Figure 4-14. Relative Heat Exchanger Volume for Gas Mixtures and Air on Shell Side and Helium on Tube Side

4.3.2 Gas Property Effects on Turbomachinery and Piping

In the turbomachinery area the criterion is the work capacity of the gas per unit volume, so that it is appropriate to compare different gases on the basis of work per mole, not per unit weight. Since the higher the maximum pressure, the smaller the turbomachinery and ducting for the same output, it is reasonable to assume the same maximum pressure and maximum temperature for all gases. The comparison basis then becomes a Bi-Brayton secondary loop with fixed inlet turbine pressure (P_3), turbine inlet temperature (T_3), fixed compressor turbine inlet ature (T_1), fixed temperature ratios across the compressor (T_2/T_1) and turbine (T_3/T_4) and with specified component efficiencies. This results in an overall cycle efficiency which is independent of the fluid.

The work of expansion done by any gas per mole is:

$$W_t = K_p T_3 \left(1 - \frac{1}{\left(\frac{P_4}{P_3}\right)^{(R/K_p)}} \right) \tag{1}$$

where K_p is the molecular specific heat. Since the turbine inlet temperature and temperature ratio is constant.

$$\left(\frac{P_4}{P_3}\right)^{\frac{R}{K_p}} = \left(\frac{T_4}{T_3}\right) \tag{2}$$

Therefore turbine work is proportional to the molecular specific heat

$$W_t \sim K_p \tag{3}$$

Because the turbine inlet pressure (P_3) is fixed and the exit pressure (P_4) is inversely proportional to the fixed temperature ratio, the work capacity per unit volume of the gas at the turbine exit or the compressor inlet is proportional to $K_p / (T_4/T_3)^{(K_p/R)}$. On this criterion, monatonic gases are superior to diatonic gases (air) by about 10 percent, while polyatonic gases are inferior, requiring an increased pressure ratio and giving less work per unit volume at the low pressure ends of the turbine and compressors. As shown above, the output per unit volume of the low pressure ends is proportioned $K_p / (T_4/T_3)^{(K_p/R)}$ or for a given output, the volumetric flow rate (Q) is proportional to

$$Q \sim \frac{\left(T_{4}/T_{3}\right)^{(K_p/R)}}{K_p} \tag{4}$$

The cross sectional flow area (A) is proportional to

$$A \sim \frac{Q}{V_a} \sim \frac{Q}{U} \tag{5}$$

where V_a is the axial velocity and U is the mean blade speed. Since the mean blade speed squared is proportion to

$$U^2 \sim \frac{C_P}{S} \sim \frac{K_p}{SM} \tag{6}$$

then the low pressure flow area

$$A \sim \frac{\left(T_{4}/T_{3}\right)^{(K_p/R)}}{K_p} \sqrt{\frac{SM}{K_p}} \tag{7}$$

The number of stages (S) are dependent on limitations set by blade speed, Mach No. and gas bending stresses.

The number of stages for limiting blade speed

$$S \sim K_p/M$$

and therefore

$$A \sim \frac{\left(T_{4}/T_{3}\right)^{(K_p/R)}}{K_p}$$

for limiting Mach No.

$$S \sim K_p \, M/\gamma$$

and where γ is the specific heat ratio

$$A \sim \frac{\left(T_{4}/T_{3}\right)^{(K_p/R)}}{K_p} \frac{M}{\sqrt{\gamma}}$$

for limiting bending stress

$$S \sim K_p$$

and

$$A \sim \frac{\left(T_{4/T_3}\right)^{(K_p/R)}}{K_p} \sqrt{M}$$

The cross sectional flow area for air and argon is about 60 percent greater than that of helium, and CO_2 requires about 3.5 times the flow area of that of helium. For the lighter gases (helium, light gas mixtures) the limiting blade speed determines the number of stages and therefore they do require many stages; however the flow area is small producing long, narrow turbonmachinery. The heavy gases fail to compete, since Mach No. or gas bending stresses limitations intervene to prevent the reduction in the number of stages which their greater density would seem to indicate.

The gas property effect on piping diameter, assuming the same pressure loss per unit length, energy transport and temperature and pressure level, is:

$$D \sim \frac{\mu^{0.0416}\, M^{0.165}}{K_p^{\;0.375}}$$

The viscosity and molar specific heat effects are small (less than 10 percent) with the result that the molecular weight (M) is controlling. For example, argon would require a piping diameter approximately 1.5 times that required for helium, and would more than double the piping weight.

The gas property effects on the Bi-Brayton system are summarized below:

- Helium has smallest intermediate heat exchangers
- Helium has smallest piping size and weight
- Helium has smallest turbo-compressor machinery cross sectional area
- Helium has the least effect due to leakage of secondary into primary work fluid.

Therefore for this Bi-Brayton application, helium has been selected for the secondary loop working fluid.

5.0 REFERENCE SYSTEM

5.1 SYSTEM

The total powerplant includes the Bi-Brayton system to provide power to the fan for nuclear propulsion, the JP fueled open cycle engine and the ducted fan. The fan can be powered by either the Bi-Brayton power turbine or the JP fueled engine, or by combined power from both nuclear and JP turbines. These are schematically illustrated in Figures 5-1 and 5-2.

The Bi-Brayton system can be considered to consist of two subsystems. These are the Nuclear Subsystem (NSS) and the secondary (or energy transport) subsystem. As illustrated in Figure 5-1, the NSS includes all components out to and including the containment vessel (and any shielding which might be installed external to the containment vessel). The secondary system includes the piping to the power turbines in the nacelles, power turbine reduction gears, and reject heat exchangers in the nacelles. Thus, the Bi-Brayton system provides the nuclear energy and transforms it into shaft power for the fan thrustor and adds the reject heat to the fan discharge airflow for additional thrust.

The reactor is a helium cooled, graphite moderated, epi-thermal reactor based upon the nuclear rocket and commercial reactor technologies. The primary helium is heated to $1800^{\circ}F$ in the reactor, passes through a plug shield which attenuates the radiation from the reactor and then is transported to the four parallel primary turbines. The primary turbines extract the work necessary to drive both the primary and secondary compressors. After expansion in the turbines, the primary helium is cooled in four counterflow Intermediate Heat Exchangers (IHX), is compressed and returned to the reactor in piping concentric with the hot leg piping.

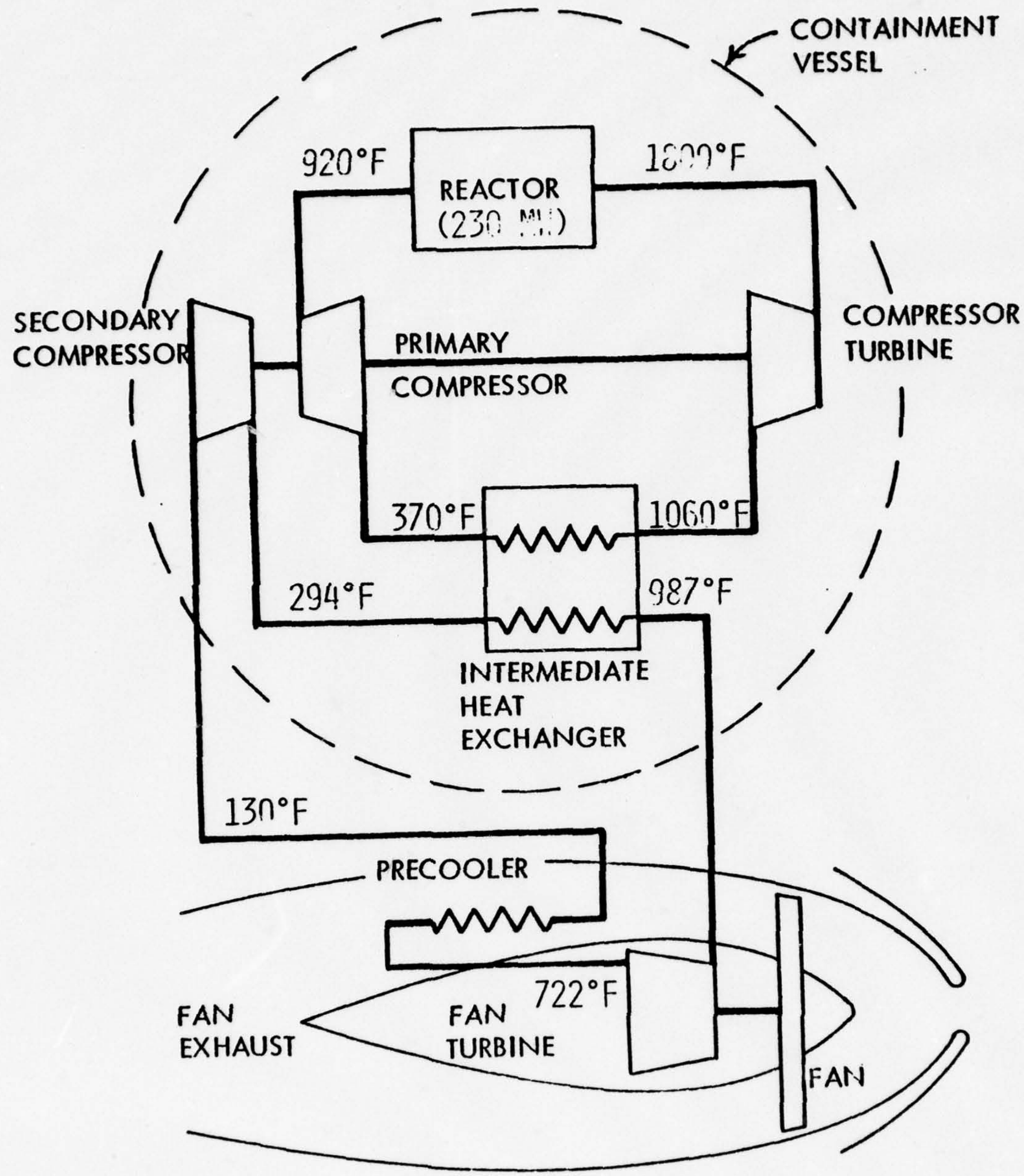

Figure 5-1. Bi-Brayton System Schematic

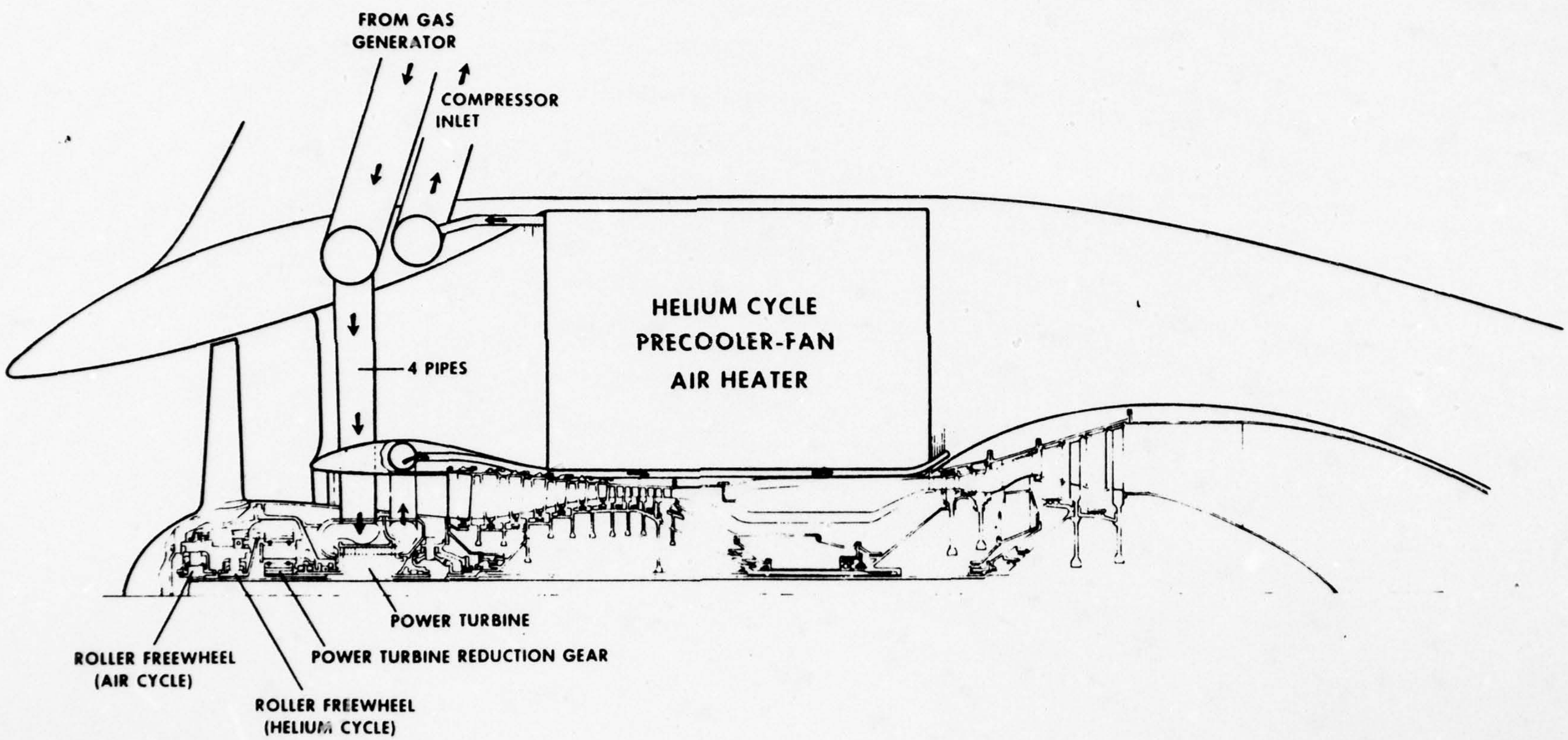

Figure 5-2. Dual Mode (Helium/Air Cycle) Ducted Fan (From Reference 1)

The secondary helium is compressed in the four parallel compressors and is heated by absorbing the energy rejected from the primary fluid in the four IHX. The secondary helium is then transported to the power turbines in the nacelles which drive the fan thrustors. After expansion in the power turbines, the secondary helium is cooled in the counterflow coolers wherein the reject heat is transferred to the fan discharge air to provide additional thrust. The helium returns to the secondary compressors via the outer piping concentric with the secondary supply piping.

Nuclear powered aircraft must be designed to have the capability of operation on either nuclear power or on JP fuel. It was determined in the Reference 1 cycle comparisons that a closed Brayton cycle power turbine and JP fueled engine could be combined as shown in Figure 5-2 to provide a "dual-mode thrustor". The JP fueled engine is therefore a normal turbofan except that the fan can be coupled to either the JP engine or the Bi-Brayton power turbine. The fan pressure ratio and airflow are sized by the nuclear cruise conditions but appear to also be reasonable for the open cycle turbofan engine.

5.2 BI-BRAYTON SYSTEM CONFIGURATION

5.2.1 Nuclear Subsystem Configuration

Containment Arrangement

Figure 5-3 shows the NSS equipment located within a 20 foot containment sphere. The reactor has been positioned with the flow up through the core for ease of supporting the reactor vessel and external shielding. This will require some modification of the reference reactor core support design, but no problems are foreseen. (If difficulties are encountered, the entire assembly will be inverted.)

The turbomachinery and heat exchangers are clustered around the reactor with their centerlines parallel to the longitudinal centerline of the aircraft. Since the turbomachines are the longer units, they were located nearest to the containment center where available chord length is greatest.

The primary and secondary piping within containment is shown on the drawing. Separate pipes to and from containment are shown, but concentric pipes could be accommodated in this design if future studies confirm the desirability of

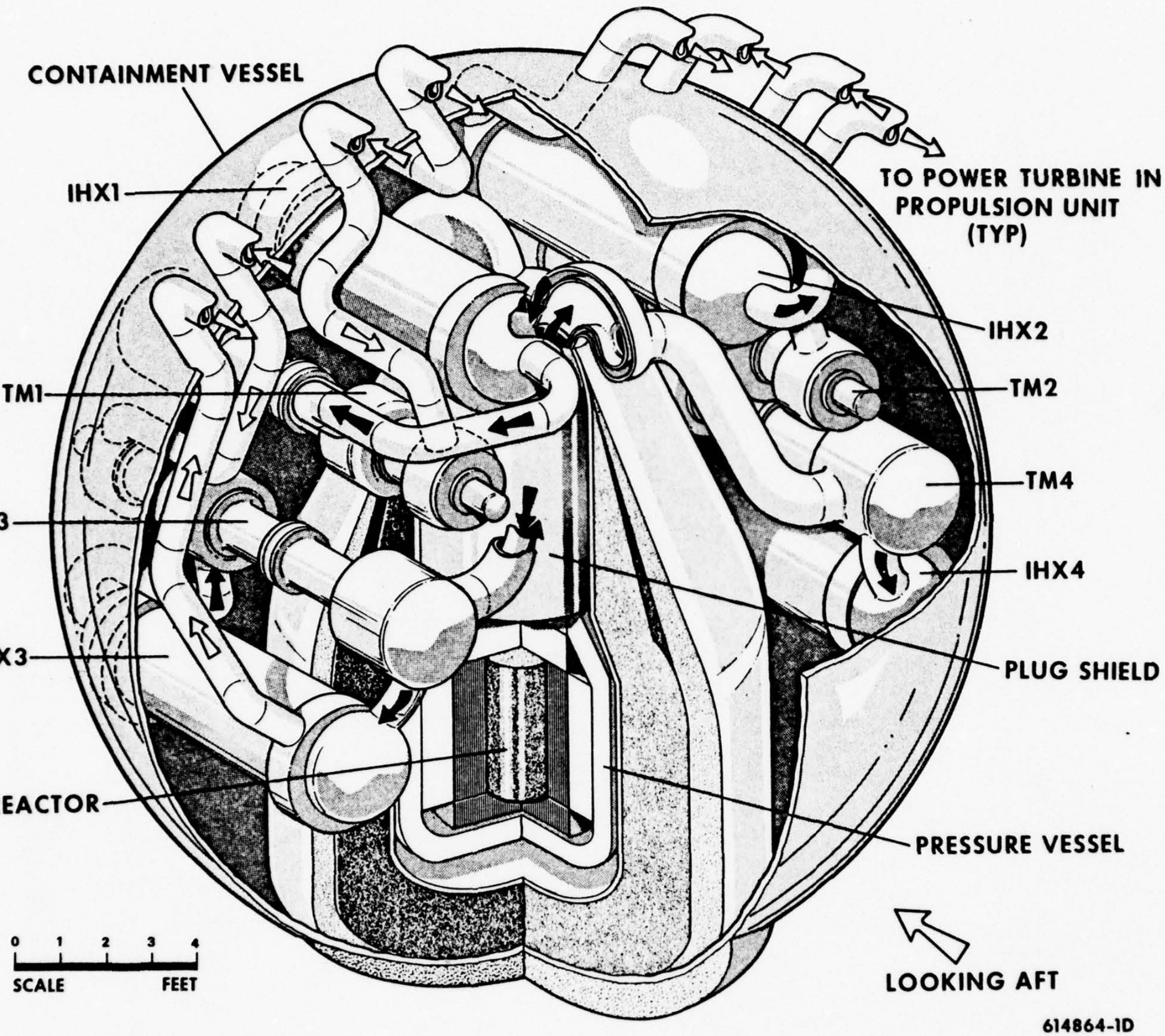

Figure 5-3. Nuclear Bi-Brayton System for Aircraft Propulsion

such. Not shown on the drawing are the containment isolation valves required at each penetration.

The containment diameter shown (20 feet) is close to the minimum required to house the components described in this study. One component which could be changed to reduce the containment diameter is the plug shield. By employing a spiral configuration for the helium piping, solid shielding could be employed to replace the plug shield. However, there are mechanical design considerations which must be addressed for the spiral configuration and demonstration of shielding effectiveness is beyond the scope of this study, so the previously derived conservative design of the plug shield has been used.

Reactor

Definition of the reactor concept was not part of this study. Reactor characteristics, dimensions and weight for the Light Weight Powerplant (LWNP) reactor concept which has been derived by Westinghouse funded in-house studies (References 3, 4 and 5) were provided as necessary to support the study. This reactor concept was defined based upon use of already existing technologies for application to marine nuclear propulsion systems. However, the reactor configuration should be optimized for aircraft applications in later studies.

The LWNP reactor is a gas-cooled, graphite-moderate epi-thermal reactor with coated fuel beads dispersed in graphite elements. It has a lateral support system to maintain core bundling and a beryllium radial reflector with control drums. The reactor design is based upon adaptation of the technology proven in the NERVA nuclear rocket reactor. While fuel element fabrication is based on NERVA technology, the lower operating temperature permits the use of TRISO design fuel beads which have been developed for commercial reactors to provide a high level of fission product retention. In veiw of the relatively low core exit temperature (1800^{o}F), a hot end support plate developed as an alternate core support design in the NERVA Program is very appropriate and is incorporated into this design.

Figure 5-4 shows the assembly oriented with the plug shield in the exhaust below the core. As stated previously, the containment arrangement appears to be more favorable with an inverted arrangement which would require some rearrangement of components within the reactor pressure vessel. The necessary rearrangements are practical, but, since reactor design was not part of this study, have not been detailed. For clarity and to illustrate one candidate reactor orientation, the reactor assembly is shown in Figure 5-4 in the marine powerplant orientation which is inverted from that shown in the NSS assembly view of Figure 5-3. Table 5-1 lists the major reactor and shield dimensions.

The reactor assembly, shown in Figure 5-4, consists of fueled core surrounded by a reflector and internal shield - the whole assembly being contained in a pressure vessel. An external shield surrounds the assembly Where the working fluid enters and leaves the reactor, a plug shield is used to limit the radiation to an acceptable level.

The reactor core is constructed from hexagonal fuel elements which are 36 inches in length. Each fuel element has seven axial cooling holes, each 0.133 inch in diameter, providing twenty percent void fraction. The elements measure 0.75 inch across the flats of the hexagon and are bundled together in the form of a right circular cylinger approximately 49.1 inches in diameter. The fuel, in the form of TRISO coated beads, is incorporated into the extruded graphite matrix of the fuel element. In amny important respects, the conditions in the Bi-Brayton system reactor are much more genign than in the NERVA reactor from which it is derived. Comparing Bi-Brayton system reactor conditions to those of NERVA reactors, the use of helium instead of the corrosive hydrogen used in NERVA, lower core exit temperature level (1800°F versus 4000°F for NERVA) and lower temperature rise between core inlet and core exit (900°F versus 4200°F for NERVA) significantly ease the environment for the core, contributing to long reactor life.

Strips of pyrolytic graphite insulation material are interposed between the filler strips and the fuel elements to minimize the radial conduction of heat from the core. The radial forces which accomplish the bundling of the core are transmitted through a system of graphite segments and steel leaf springs to the reflector assembly which surrounds the core.

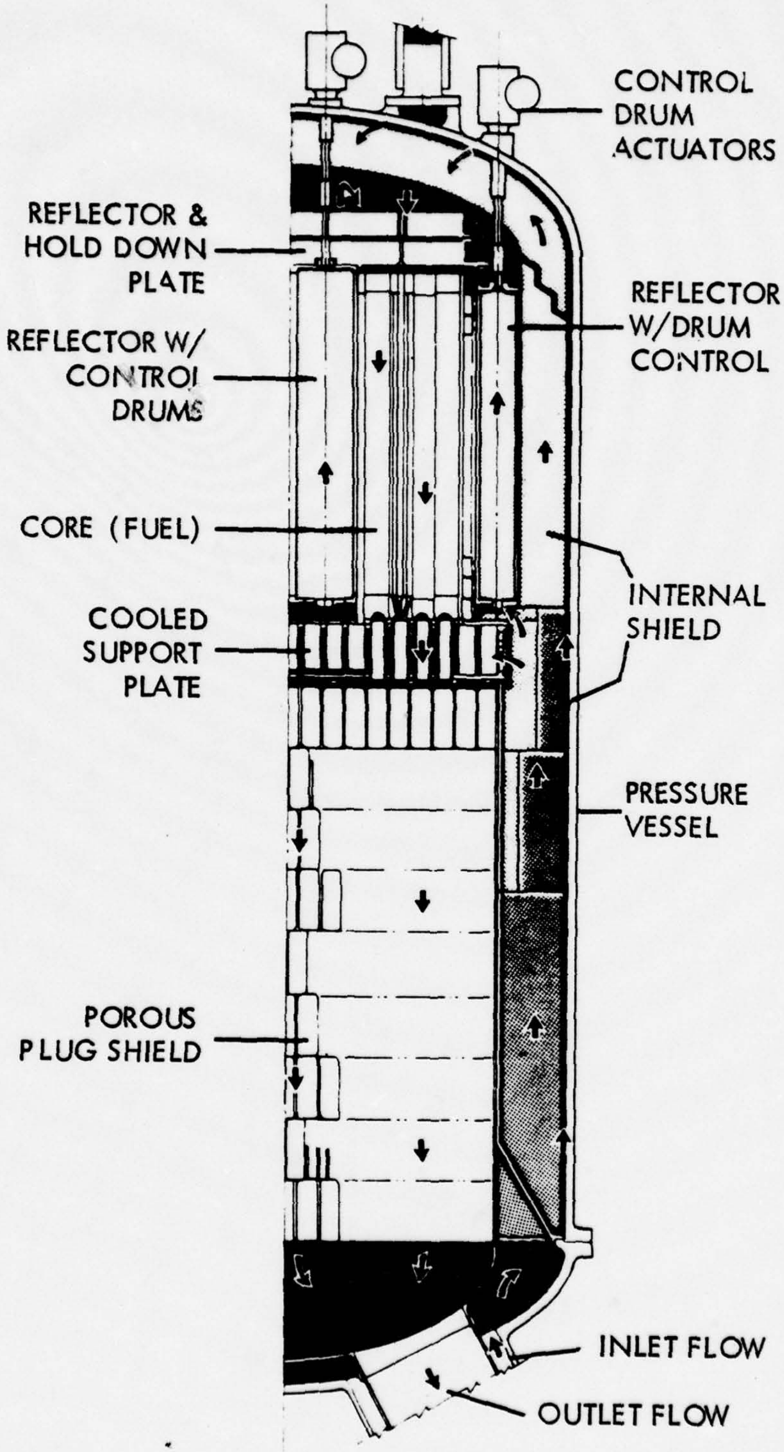

Figure 5-4. LWNP Reactor

TABLE 5-1

NUCLEAR SUBSYSTEM GEOMETRY AND WEIGHT SUMMARY
(230 MW)

Reactor Radial Dimensions	Outer Diameter (Inches)	Thickness (Inches)
Core	49.11	
Filler Strips	50.61	0.75
Lateral Support	54.41	1.90
Beryllium Reflector	66.41	6.00
Tungsten Shielding	81.16	6.88
Pressure Vessel	85.16	3.00
Reactor Fueled Core Length (Inch)	36.00	
Outer Shielding Thickness (Inch)	31.00	
Zirconium Hydride		
Primary Radial Direction	31.00	
Transverse Radial Direction	19.80	
Vertical Direction	17.90	
Lithium Hydride		
Primary Radial Direction	14.00	
Transverse Radial Direction	11.60	
Vertical Direction	6.20	

Reactor-Shield Weight Summary (Lb)	
Reactor	4,240
Beryllium Reflector	2,410
Tungsten Shielding	75,180
Pressure Vessel	19,930
Zirconium Hydride Shielding	182,140
Lithium Hydride Shielding	19,390
Support Plate	6,520
Plug Shield	41,120
Containment Vessel	109,980

The reflector assembly which surrounds the core is constructed from twenty-four beryllium segments which are bolted to Inconel 718 rings at the inlet and outlet ends. Each segment contains a control drum which can be rotated through an angle of 180 degrees. The control drum consists of a beryllium cylinder having a sector of beryllium removed and replaced by a number of stainless steel tubes containing boron carbide. The control drums are driven through splined quill shafts from electric actuators mounted on the pressure vessel dome. Axial cooling holes are drilled in the reflector segments and control drums.

A reflector assembly with control drums is also provided at the center of the core for additional reactivity control to compensate for reactivity changes due to U235 burnup. This reflector is similar in design to the outer reflector.

The pressure vessel is a hollow cylinder with elliptical heads. It is made from two weldments which are joined by means of a bolted and seal-welded flange. The outlet head is penetrated by two nozzles which convey the reactor coolant to and from the heat exchanger and turbomachinery modules. A coaxial flow system is employed at each nozzle, the hot gas leaving the reactor through the central Inconel X pipe. The pressure vessel and piping walls which must withstand the system operating pressure are therefore exposed only to the cooler reactor inlet gas flowing in the outer annular space.

Structural sizing of the pressure vessel has been predicated on an operating pressure of 1600 psi, and an allowable material stress of 30,000 psi. This is consistent with the use of SA-533 Low Alloy Steel which is generally used throughout the nuclear industry for coded pressure vessels. Substitution of Inconel 718 for the pressure vessel in this application offers the potential of increased strength capability or a reduction in pressure vessel thickness.

Shielding

Radiation shielding is provided internal to the pressure vessel and acts with the external shielding to satisfy the applicable dose rate criteria. The light weight layered shielding design is adapted from the Reference 6 NuERA shielding optimizations. The internal shield is composed of two parts: a tungsten or de-

pleted uranium gamma shield that surrounds the radial and bottom reflectors, and the separate plug shield (neutron and gamma).

The tungsten internal shield is constructed from segmental blocks which are provided with cooling holes and are supported from Inconel 718 rings. This shielding is located internal to the pressure vessel for ease of cooling, to recover the energy deposited in it, and is advantageous in minimizing total shield weight.

The plug shield consists of cans or capsules of mixed boron carbide, tungsten, and beryllium oxide strung axially the length of the plug in a tight over-lapping matrix. Gas flows around the capsules while radiation is attenuated by them.

The primary shield (external to the pressure vessel) completely encloses the reactor, and consists of an inner layer of borated zirconium hydride and an outer layer of lithium hydride. Inserted between these two major layers is a sheet of boral. The shield is compartmented and hermetically sealed because of materials outgassing and the need to contain the shield coolant.

Turbomachinery Configuration

The general configuration and sizing of the gas generator turbomachinery was developed by appropriately scaling from similar components developed in a Compact Closed Cycle Brayton System (CCCBS) study performed for ONR (Reference 7). The cycle temperature and pressure state points and the component sizes used in the Reference 7 study, which also used a helium working fluid, are quite similar to the Bi-Brayton condition. The resulting Bi-Brayton components, therefore, benefit from the substantial research effort applied to the ONR program. Figure 5-5 shows the turbomachinery assembly.

The design work generated in the Reference 7 program was based on earlier work on helium turbomachinery performed by Westinghouse for the Maritime Administration on the Marine Gas Cooled Reactor (MGCR) Project in 1962. This work included the design of a complete closed cycle power plant using helium gas as the working fluid and the testing of the most critical components of

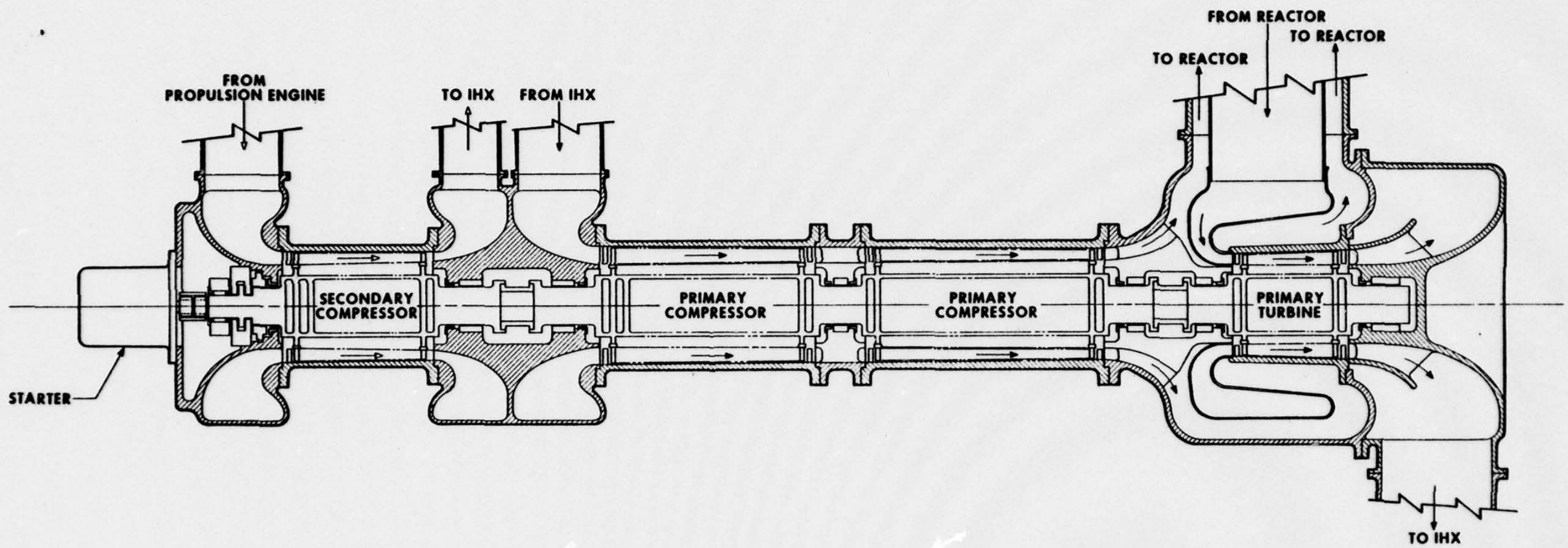

Figure 5-5. Bi-Brayton Turbomachinery Assembly

the system. During the MGCR program, extensive testing was conducted on a two stage turbine test model, a four stage compressor test model and on component inlet ducting. Tests were also conducted on bearing and seal components to investigate the compatibility of lubricants with the helium working gas under practical operating conditions. No problems were encountered due to foam or mist generation.

The MGCR power plant turbomachinery components exhibited the relatively large numbers of stages, compared with typical air cycle machinery, needed to achieve the nominal pressure ratios required in the plant cycle. Since these designs were thoroughly worked out and achieved good efficiencies (0.90 turbine and 0.85 compressor as verified by component testing) the MGCR design work provided a good basis for the ONR Closed Brayton Cycle component designs which in turn provides the basis for the Bi-Brayton turbomachinery concept.

In developing the compressor components of the ONR Closed Brayton System from the MGCR work a scaling process was used which assumed the $\Delta P/P$ per stage to be directly proportional to the square of the mean blade speed and inversely proportional to the mean gas temperature. For flow path sizing, the flow coefficient of 0.5 used in the MGCR compressor designs was retained, resulting in an axial velocity equal to half the mean blade speed. Mean blade speed was limited to a maximum of 1350 ft./sec. in the low pressure compressor. Hub/tip ratio was limited to a maximum of 0.85 to avoid excessive blade tip loss effects. This latter restriction resulted in the mean blade speed of the high pressure compressor being reduced to approximately 1100 ft./sec. The lower work per stage and consequently increased number of stages required in the high pressure compressor was accepted as a necessary compromise of the compactness of the machinery to ensure the achievement of the assumed efficienty (85 percent). The resulting numbers of stages in the low pressure and high pressure compressors were 14 and 18 respectively.

In deriving the Bi-Brayton compressor components, a similar scaling process was employed. However, as a result of the higher average temperature level in the Bi-Brayton primary compressor, the required total number of stages increased

from 32 to 40 at a uniform mean blade speed of 1350 ft./sec. No reduction in mean diameter (and mean blade speed) was required to limit hub/tip ratio, a value of approximately 0.85 being reached in the outlet stages.

In laying out the Bi-Brayton primary compressor, the 40 stage assembly was judged to be excessively long from considerations of rotor dynamics and stability. As a result, the compressor was split into two components separated by a bearing and coupling assembly. A similar bearing and coupling assembly was interposed between the secondary compressor outlet and the primary compressor inlet.

The Bi-Brayton secondary compressor scaling from the ONR low pressure compressor, required 12 stages at the same mean blade speed of 1350 ft./sec.

In designing the high pressure (compressor drive) turbine for the Reference 7 ONR Closed Brayton System, special measures were taken to minimize blade centrifugal stresses and thus permit the achievement of a relatively high inlet temperature (1670°F) with uncooled superalloy blading. The resulting blade had relatively high load and flow coefficients resulting in a mean blade speed of 1200 ft/sec and a first stage hub/tip ratio of 0.81. Five stages were required. The use of high load and flow coefficients results in some efficiency penalty and this was estimated for the above design using an empirically based correlation extracted from P.127 of Axial Flow Turbines - Fluid Mechanics and Thermodynamics by J. H. Horlock (1966 Butteroworth). The overall efficiency of the ONR high pressure turbine was estimated to be 89 percent accounting for blade tip and bearing losses.

In deriving the Bi-Brayton primary system turbine from the ONR high pressure turbine, the mean blade speed of 1200 ft./sec. and the hub/tip ratio of .81 were retained and the number of stages was increased from 5 to 9 maintain essentially the same temperature drop per stage (85-80°F).

Having defined the turbine and compressor stage complements and the general configuration of the Bi-Brayton turbomachinery, the sizing of the units was developed by scaling component linear dimensions in proportion to the square

root of the mass flow. As a result, to maintain mean blade speed, RPM was increased inversely as the linear dimension. Using this process, blade centrifugal stresses remain unchanged, since mean blade speed and hub/tip ratio are maintained. When the axial dimensions are scaled in the same ratio, blade bending stresses remain constant. Since weight is proportional to linear deimsnion cubed and power is proportional to flow rate which is proportaional o linear dimension squared, scaling turbomachinery downward in size results in reduced specific weight.

Initially the Bi-Brayton primary system turbomachinery units were sized assuming that two units would be used to supply the four propulsion engines. The rotational speed of these units was approximately 20,930 RPM. However, the size of these units proved to be too great to permit their incorporation into a containment vessel with the reactor and intermediate heat exchanger units. Consequently four gas-producer systems were adopted, each unit being a $\sqrt{2}$ scale reduction in size from the two unit components. The rotational speed of the units increased from 20,930 RPM to 29,600 RPM.

The power turbine design used in the four propulsion units was obtained by scaling the ONR study power turbine form its 70,000 HP value to the 25,000 HP size required for each of the four Bi-Brayton thrustors. This was judged to be sufficiently accurate for initial concept generation since pressure ratios and state points were comparable. Since power is proportional to flow rate which is proportional to the square of the linear diemsnion, the power scaling factor was 0.36 resulting in a linear dimension scaling factor of 0.6. The RPM was therefore increased from 6,000 RPM to 10,000 RPM to maintain the same blade speed. Since fan speed was roughly 2,500 RPM a reduction gear of approximately 4:1 ratio was required, thus confirming the general layout of the propulsion units developed in the earlier study.

Intermediate Heat Exchanger Configuration

The four Intermediate Heat Exchanger (IHX) units of Figure 5-6 employ the same design approach as the Reference 7 ONR study recuperator modules. A counterflow shell and tube configuration with 0.120 inch O.D. x 0.010 inch thick tubes on a

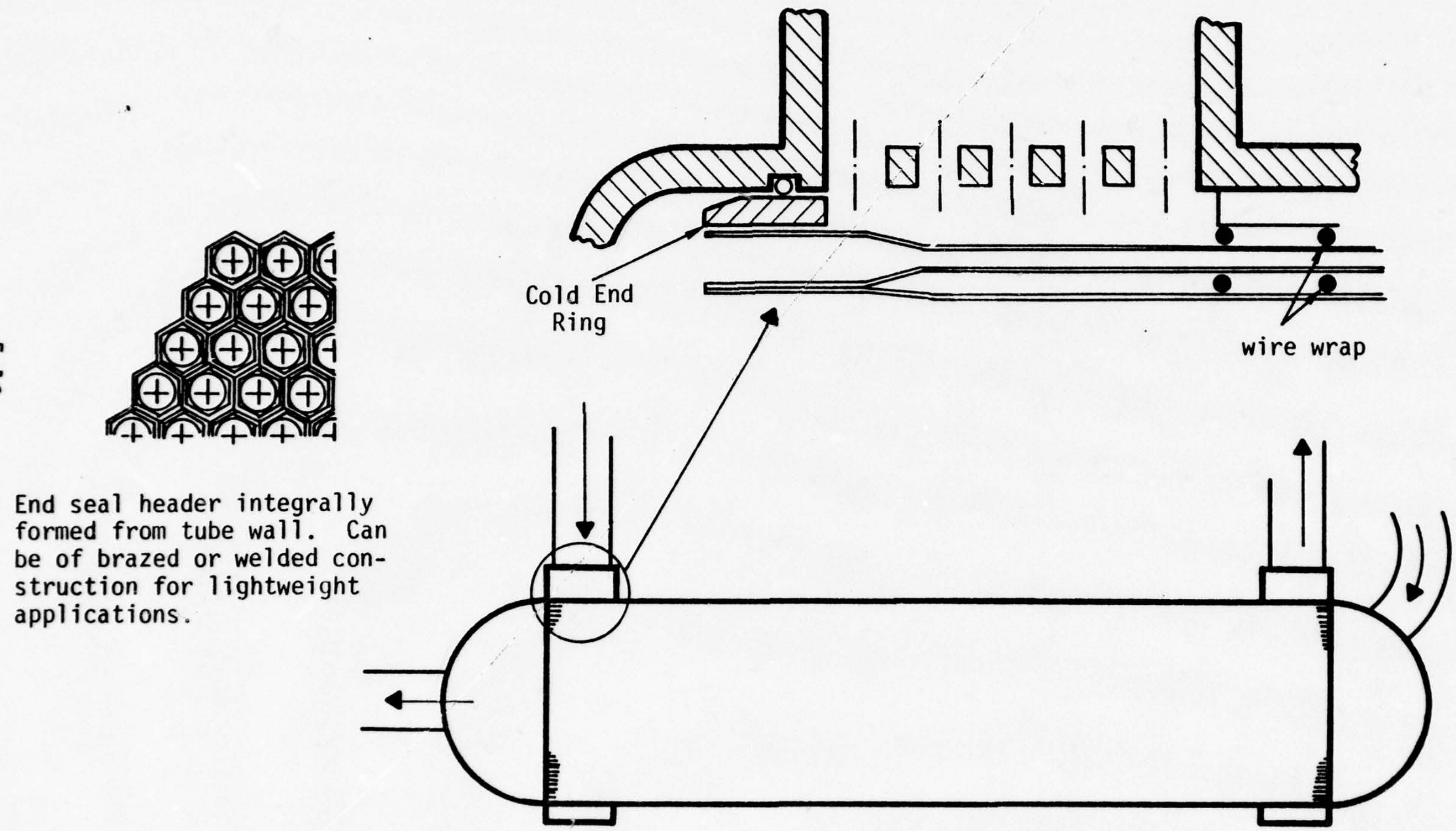

Figure 5-6. Intermediate Heat Exchanger Module Concept Using Hex Ended Tubing

triangular pitch and 1.30 pitch/diameter ratio is used. Tube length is 89.3 inches and the tube matrix outer diameter is 28.3 inches. Tube spacing is maintained along the heat transfer length by means of spirally wound wires. The spiral wires are discontinued in the region at each end of the heat transfer length to allow cross flow to and from the shell side headers which are formed as semi-toroidal circumferential additions at each end of the shell cylinder.

The tube nest is relieved of the thermal stresses in the axial direction by being permitted to float freely at the cold end. The plate into which the tubes are brazed is sealed to the shell by a large diameter O-ring at the cold end. The hot end plate is fixed to the shell by a bolted flange. The hemispherical ends which form the tube side headers are attached to the shell by bolted flanges to facilitate assembly and provide access to the tube nest.

In this design the plates into which the tubes are brazed are essentially unstressed in bending and each tube supports its local increment of plate in the axial direction. The removal of bending loads from the plates allows other fabrication approaches to be considered which avoid the need for drilling the large numbers of tube location holes in the plates. The plates in one such approach are eliminated completely by forming the ends of the tubes into a hexagonal section allowing them to be brazed together. A furnace brazed assembly, using microbraze applied as paste to the tube ends prior to fixturing can be envisioned. It is believed that the adoption of such approaches in fabrication of fine geometry light weight heat exchangers can be cost effective.

As discussed above, compact tube-type heat exchanger characteristics have been used. However, it should be recognized that compact plate-and-fin type heat exchangers were also shown to be attractive in the Reference 7 study and should be considered a practical alternate for a Bi-Brayton system. Trade studies would be required to select between the two types.

Secondary Piping

The use of helium (gas) for the secondary working fluid in the Bi-Brayton Cycle allows the use of concentric piping from the containment vessel to the engines. The inner pipe (11.39 inches O.D.) has a liner inside this pipe, with a gap of 0.20 inch, to prevent significant heat transfer from the hot gas to the cooler gas. The outer pipe has a diameter of 17.78 inches with a thickness of 0.133 inch. The total concentric piping weight is 37.5 lb/ft. If separate piping were used, the insulation for the hot pipe by itself would weigh more than 37.5 lb/ft. The total piping length for the four engines is 606 feet, which results in a piping weight of 22,725 pounds.

Engine Precooler Heat Exchanger

The engine precooler heat exchanger is a counterflow bore tube exchanger wherein the reject heat is transferred to the fan discharge air to provide additional thrust. The secondary helium flows inside the tubes where it is cooled from 722^{o}F to 120^{o}F. The fan air enters the shield side of the heat exchanger at 59^{o}F. and is heated to 199^{o}F. The heat exchanger is annular shaped to fit around the engine turbomachiners (Figure 5-2) and is enclosed by the nacelle. The tubes are placed on a triangular pitch of 1.107 inch. The tubes have a 0.2075 inch outer diameter and 0.1875 inch inner diameter and are 119 inches in length. The annular cross sectional area of the precooler is 128 ft.^{2}.

Controls

Although control system definition studies were not part of this study, the results of other studies were considered and a reference control system identified for use in overall system feasibility evaluation.

The reference case requirements are for use of the nuclear propulsion system only for cruise. Therefore, the normal operation power range is approximately from 80 to 100 percent of full power. This range is sufficiently narrow and the primary and secondary system so closely coupled that reactor control should accomplish almost all of the overall system control needed. The secondary system control needed should be more in the nature of a trim. Of course, trim and shutoff capability for each power turbine will be needed.

The reference conceptual control system therefore includes primary system control by maintaining a scheduled reactor outlet temperature. Reactor control is accomplished by means of the radial reflector control drums. Overall secondary system control is by inventory control whereby helium is bled from or added to the system to accomplish output power reduction or increase. There are other alternatives to inventory control, and more detailed studies would be required to select between the various alternatives. The alternatives include turbine bypass bleed, compressor bleed, in line hot-leg throttling and in-line cold-leg throttling.

Because gas is used as the working fluid in both primary and secondary systems and because of the demonstrated startup capability of this type of reactor, automatically controlled rapid startup of the powerplant can be planned.

5.3 CHARACTERISTICS

5.3.1 Reference Case

The state points for the reference case nuclear Bi-Brayton system are tabulated in Table 5-2. State points are included for the primary and secondary helium systems and for the fan air stream. Reactor power for this case is 230 MW.

High temprature turbomachinery for this application will require bleed flows for cooling, and realistic system sizing must include allowances for such cooling. Although detailed turbomachinery designs would be necessary to accurately define the cooling flows required, the cycle state points of Table 5-2 include the effects of estimated bed flows to be realistic. In these data, the following bleed flows were assumed:

- Two percent for rotor and stator cooling
- One percent for blade cooling
- One percent for shroud cooling
- One percent for balance piston

The data of Table 5-2 also include the calculated heat loss from the hot leg to the cold leg fluid in the concentric piping. These calculations include the insulation effects of a thin liner to provide a stagnant gas layer inside the hot leg piping. The hot leg piping material temperature is then very close to the temperature of the secondary fluid.

A weight comparison between the Reference 1 NuERA reactor with open Brayton cycle engines and the LWNP reactor Bi-Brayton system in shown in Table 5-3. This table compares total powerplant and fuel weights for the aircraft from the IADS, Task II Reference Case (Table 5.2 of Reference 1).

TABLE 5-2

STATE POINTS FOR NUCLEAR BI-BRAYTON SYSTEM
FOR AIRCRAFT PROPULSION
(230 MW)

	PRESSURE (PSIA)	TEMPERATURE (°F)	FLOW RATE* (LB/SEC)
PRIMARY			
REACTOR INLET	1576	920	199.0
REACTOR OUTLET	1500	1800	199.0
TURBINE INLET	1489	1780	201.1
TURBINE OUTLET	496	1064	205.3
INTERMEDIATE HEAT EXCHANGER INLET	494	1060	209.5
INTERMEDIATE HEAT EXCHANGER OUTLET	478	370	209.5
COMPRESSOR INLET	476	370	209.5
COMPRESSOR OUTLET	1580	920	205.3
SECONDARY			
COMPRESSOR INLET	400	130	209.5
COMPRESSOR OUTLET	719	294	209.5
INTERMEDIATE HEAT EXCHANGER INLET	718	294	209.5
INTERMEDIATE HEAT EXCHANGER OUTLET	712	987	209.5
POWER TURBINE INLET	708	977	209.5
POWER TURBINE OUTLET	407	722	209.5
REJECT HEAT EXCHANGER INLET	406	722	209.5
REJECT HEAT EXCHANGER OUTLET	403	120	209.5
AIR			
AMBIENT	4.36	-48	4774
FAN INLET	6.34	-2	4774
FAN OUTLET	9.51	59	4774
REJECT HEAT EXCHANGER OUTLET	9.31	199	4774
NOZZLE THROAT	4.92	89	4774

* Total Flows; For Each Engine, Divide by 4

TABLE 5-3

POWERPLANT AND FUEL WEIGHT SUMMARY COMPARISON

	WEIGHT - LBS		
	Reference 1 NuERA Open Brayton	Reference Gas Cooled LWNP Bi-Brayton	Estimated Optimized Gas Cooled LWNP Bi-Brayton
Nuclear Subsystem (NSS)	391,260	494,280	419,280
NSS Auxiliaries	14,978	14,990	14,990
Int. Piping & Engine Hex	122,711	32,300	32,300
Power Turb. & Gearing		6,440	6,440
Engines	81,042	70,270	70,270
Fuel System	3,137	3,137	3,137
Fuel	134,610	122,100	122,100
Total Powerplant & Fuel	747,738	743,517	668,517

The first column of Table 5-3 lists the NuERA system weights. The second column lists the weights for the reference Bi-Brayton system, as described in this section. There is very little difference in the total of powerplant and fuel weights for the NuERA and reference Bi-Brayton systems. This is in itself important because it indicates that the benefits of the Bi-Brayton system coupled to a gas-cooled reactor of already demonstrated technology can be achieved without a powerplant weight penalty. Comparison of the first two columns of Table 5-3 indicates that the Bi-Brayton system provides a considerable savings in the categories of heat exchangers, piping and power conversion.

Since this study did not include optimization of reactor and shielding, the Nuclear Subsystem (NSS) weight shown in the second column of Table 5-3 is known to be too high. As in indication of the weight reductions that would be shown by NSS optimization, an estimate was also made of what the NSS weight would be if a "spiral pipe" shield penetration (similar to that shown in Reference 2) were substituted for the reference plug shield configuration. It was estimated that this change would reduce the shield weight and would also allow a reduction in containment diameter of approximately one foot. This change alone would result in a NSS weight reduction of approximately 67,000 pounds. Other reactor optimization such as void fraction, core length-to-diameter ratio, etc., coupled with shield optimization are expected to result in a NSS weight as shown in the third column of Table 5-3. Because the third column is a realistic extimate of what an optimization study would show the Bi-Brayton powerplant weight to be, it is recommended that this weight be used in any aircraft studies.

The systems may also be compared in some of their impacts on developments required. The NuERA liquid metal reactor is conceptual and requires intermediate liquid-metal to liquid-metal heat exchanger temperatures up to 1800^{o}F and liquid-metal to air heat exchanger temperatures up to 1700^{o}F. The Bi-Brayton system requires intermediate gas to gas heat exchanger temperatures on only 1060^{o}F, and gas to air heat exchanger temperatures less than 800^{o}F. The containment penetrations for the NuERA must be designed for 1700^{o}F liquid metal fluid temperatures, compared to about 1060^{o}F helium temperature for the Bi-Brayton system.

5.3.2 Characteristics Versus Power

In this study a reactor full power operating lifetime of 10,000 hours was used. Other parameter values used for this study included: a core outlet temperature of 1800°F and a dose rate criterion of 5mr/hr at 20 feet forward and aft of reactor centerline during operation and 5mr/hr at 20 feet in any direction 30 minutes after shutdown. An impact velocity of 250 ft/sec. was used for establishing the containment vessel thickness.

Using the above parameters, the component weights and dimensions were calculated for various reactor power levels. The nuclear subsystem weight (all components out to and including the containment vessel) and the containment outer diameter variations with reactor thermal power are shown in Figures 5-7 and 5-8 as functions of rated reactor power.

5.3.3 Effects of Component Characteristics

The NERVA derivative reactor has the capability of exit gas temperatures greater than 1800°F but the first stages of the primary turbines are the most temperature limiting components. However, the possibility exists that higher turbine inlet temperature capability from 1800°F may be achievable. The freedom from oxidation in the closed Bi-Brayton cycle and the helium working fluid allows refactory metals to be considered. MO-TZM has demonstrated the excellent forgeability required to produce the airfoil shapes and has a potential temperature capability between 1800 and 1900°F. Fiber reinforced superalloys probably have the highest strength and temperature capability of any metal systems with a potential temperature capability approaching 2000°F. Ceramic turbine blades are being developed and have a potential temperature capability of 2400°F.

The effect of increased reactor exit (turbine inlet) temperature on required power is shown in Figure 5-9. Increasing the reactor exit temperature from 1800°F to 2100°F results in approximately a 9 percent reduction in reactor power (constant thrust requirement), which results in about 3 percent reduction in powerplant weight. Increasing the reactor exit temperature to 2400°F

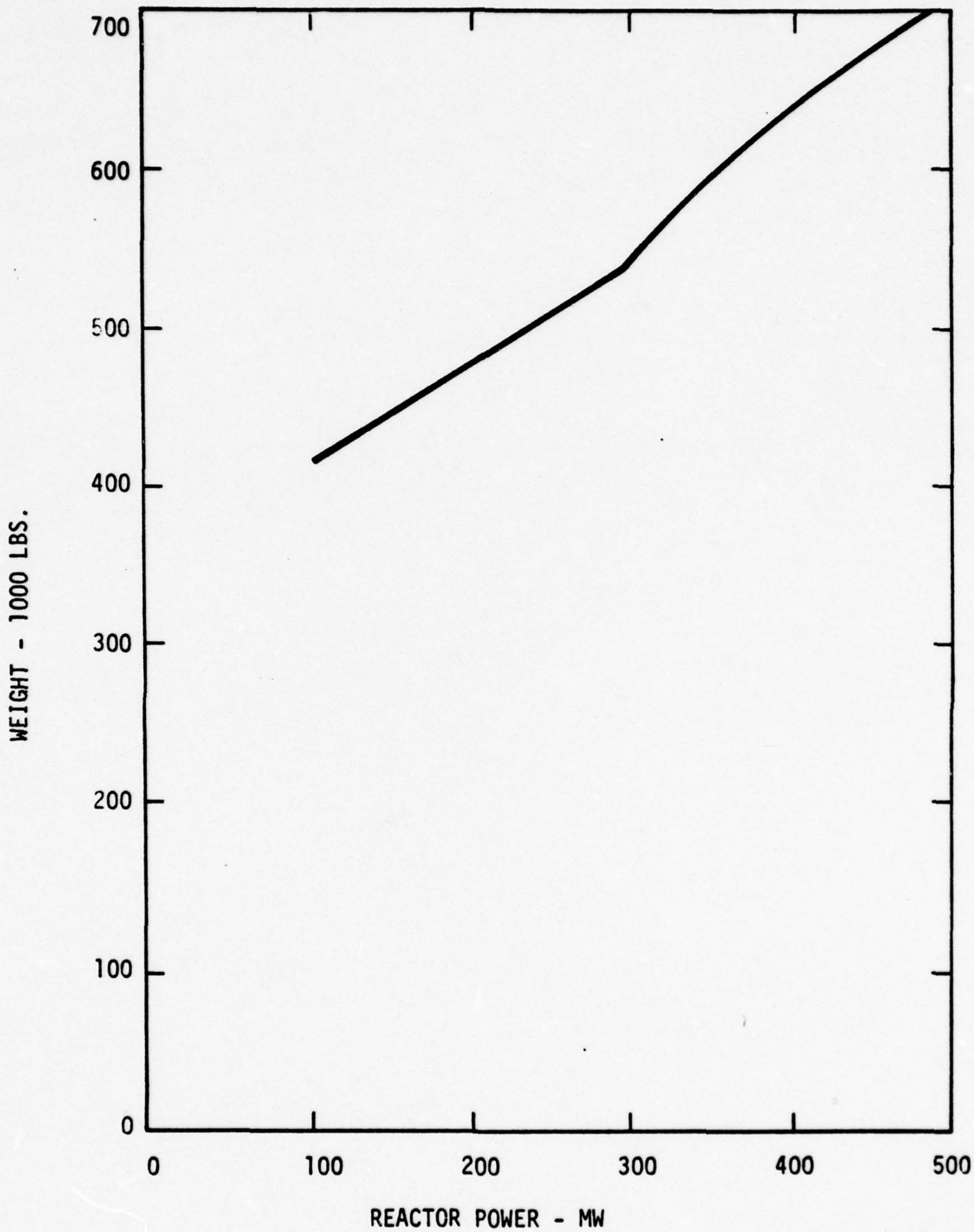

Figure 5-7. LWNP - Bi-Brayton Nuclear Subsystem Weight Variation

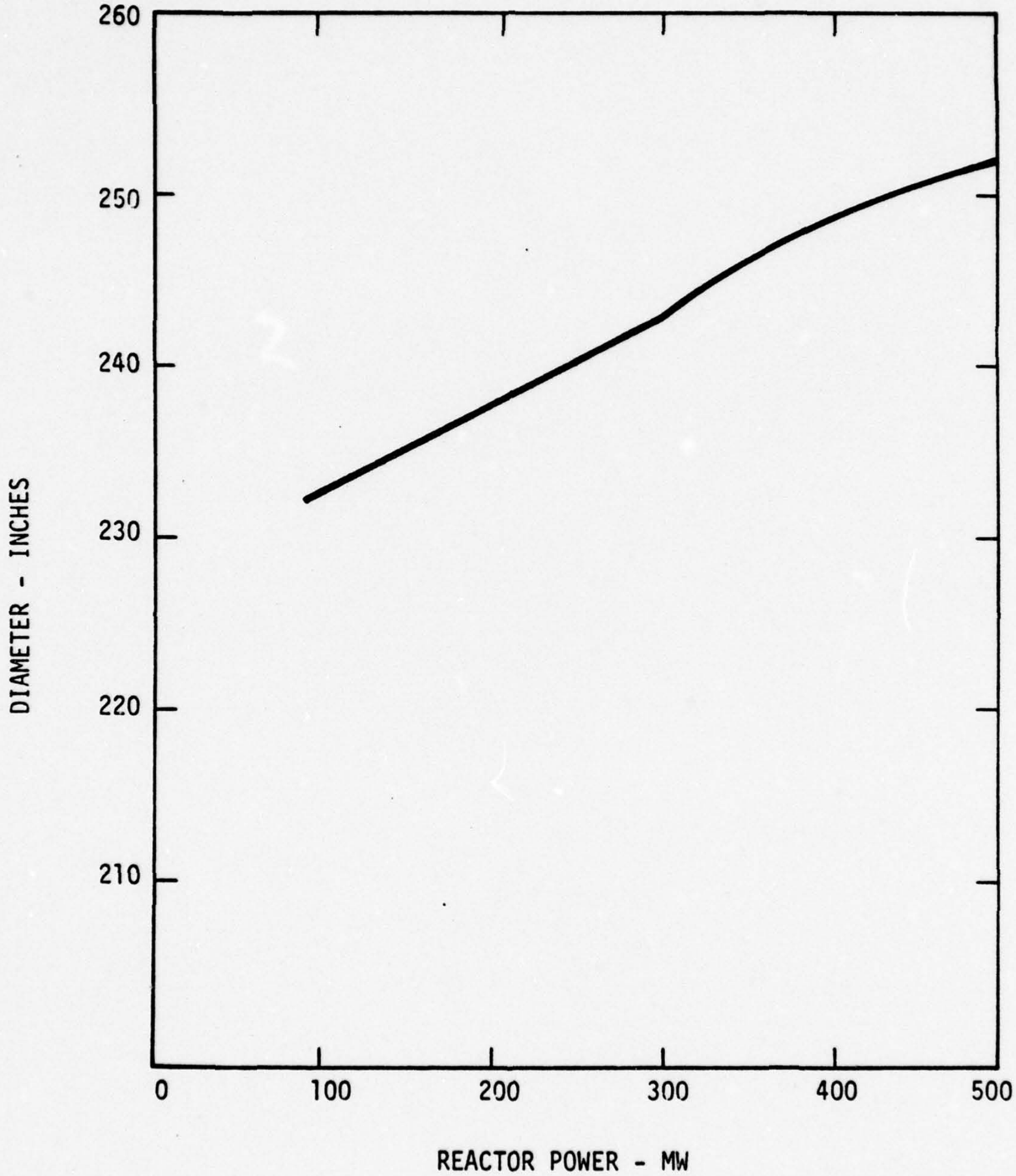

Figure 5-8. LWNP Bi-Brayton Containment Vessel Outer Diameter Variation

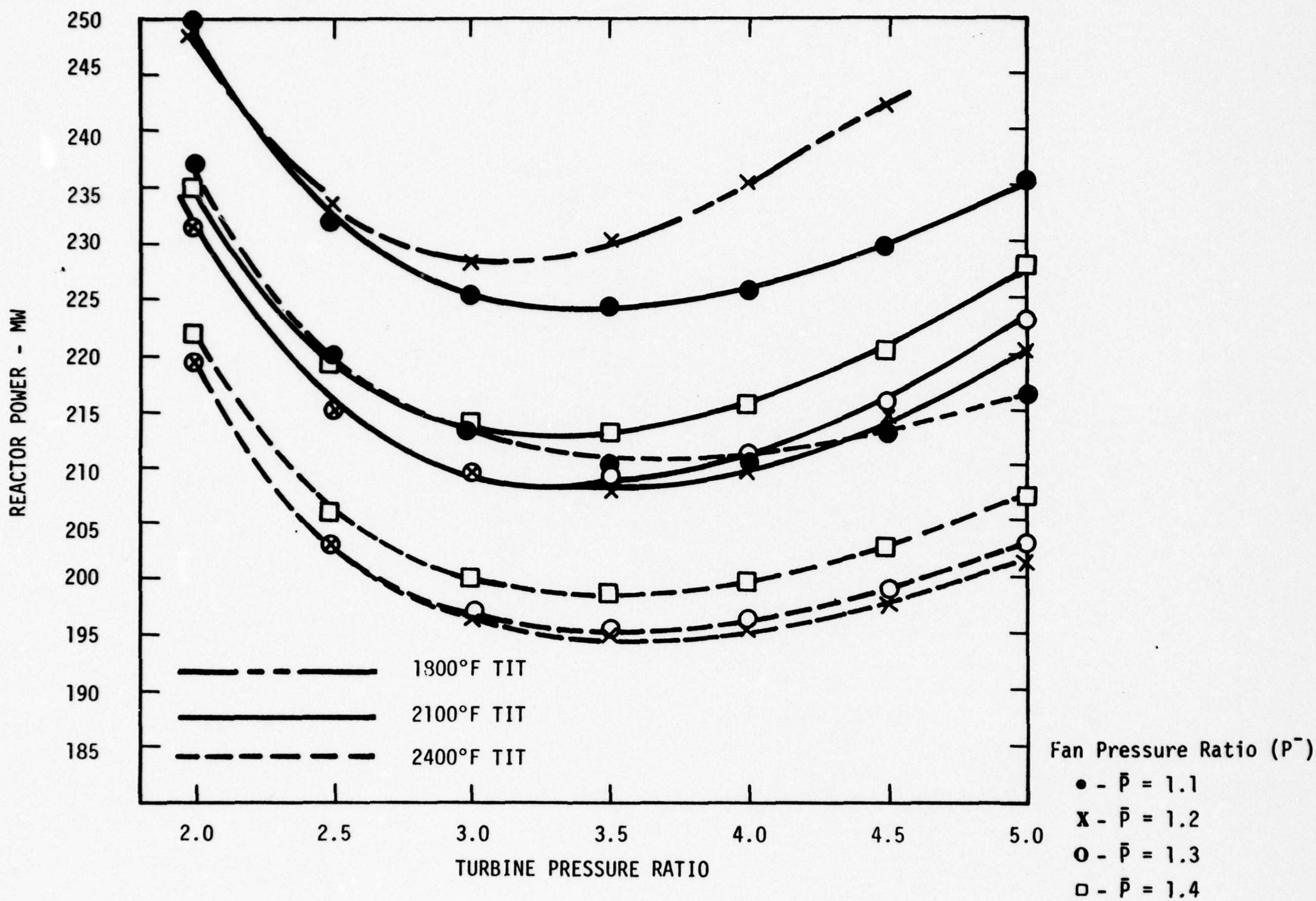

Figure 5-9. Effect of Turbine Inlet Temperature on Reactor Power (Constant Thrust)

results in a reactor power reduction of about 15 percent with a powerplant weight reduction of about 7 percent.

With today's technology, turbine efficiencies of 0.91 and compressor efficiencies of 0.88 appear reasonable. In the 1990-2000 time frame, potential turbine efficiencies of 0.93 and compressor efficiencies of 0.90 can be expected. Turbine efficiencies of 0.93 and compressor efficiencies of 0.90 were used in this study. The effect of these efficiencies is shown in Figure 5-10. A reduction of turbine efficiency from 0.93 to 0.91 and a reduction in compressor efficiency from 0.90 to 0.88 in the Bi-Brayton system results in an increase in required reactor power of about 10 percent and an increase in powerplant weight of about 3 percent.

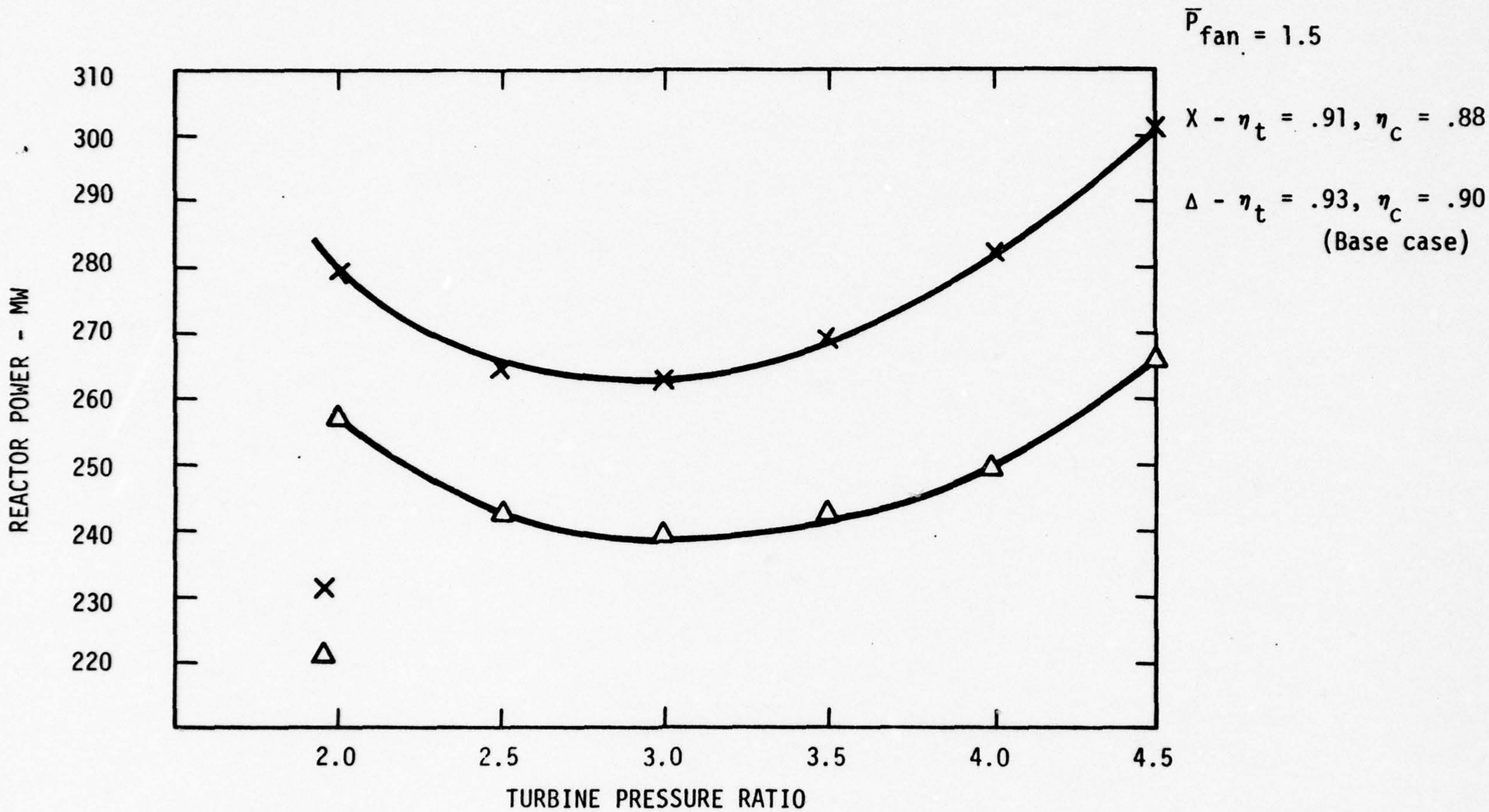

Figure 5-10. Effect of Turbine and Compressor Efficiencies on Reactor Power (Constant Thrust)

5.4 DISCUSSION OF RESULTS

The purpose of this study was to provide a preliminary definition and evaluation of the Bi-Brayton system concept utilizing an advanced high temperature gas-cooled reactor. An additional purpose was the examination of the concept of a removable containment vessel.

Specific technical results have been discussed in the sections of this report wherein they are reported. In addition, the individual results can be coupled with the results of other nuclear aircraft studies to provide the basis for the overall observations which are contained in this section. In fact, consideration of these results in the context of other study results is important because the Bi-Brayton system concept itself was derived in response to the need for certain desirable characteristics which became apparent through those earlier studies.

One of the considerations which led to definition of the Bi-Brayton system concept was the desire to minimize the developments required for the Intermediate Heat Exchanger (IHX). A requirement has been imposed in all recent studies of nuclear aircraft propulsion systems that the reactor primary system be enclosed by a containment vessel. This results in the need for a secondary system to transport the energy from the Nuclear Sybsystem (NSS) to the thrustors. Typically, the powerplant configurations of past studies have required that all of the energy used to generate thrust be transmitted through an intermediate (primary-to-secondary) heat exchanger at a temperature level as close to reactor outlet temperature as possible. Because the intermediate heat exchangers must be located inside the containment vessel, it has been necessary to minimize the dimensions of the heat exchangers so as to minimize the containment vessel diameter. Although a gas is attractive for an intermediate fluid, the power that would be required for pumping a gas typically have resulted in the identification of a liquid metal (such as NaK 78) as the secondary fluid. This has been the case whether the reactor has been liquid metal cooled, as the Reference 1 reference system and cycle comparison systems, or gas cooled, as in the Reference 2 study. Thus, a typical configuration in past studies has included intermediate heat exchangers inside the containment vessel with NaK secondary fluid to transport the energy to the thrustors.

These studies of the Bi-Brayton system concept have confirmed the validity of an alternate system which provides for separation of the primary and secondary fluids, but which limits temperatures in the heat exchanger to less than 1100°F thereby markedly reducing the problems in design and development of the intermediate heat exchanger. This system concept also provides for efficient use of an inert gas as the secondary fluid which reduces the problems in design and development of the secondary system and would reduce the consequences if a leak should occur. Comparisons of some of the powerplant characteristics with the IADS Task II NuERA powerplant are shown on Table 5-4. This comparison illustrates that a Bi-Brayton system significantly eases many of the component and material development problems.

Another aspect of the Bi-Brayton system concept which can be an advantage is its compatibility with a gas cooled reactor adapted from already provem commercial and rocket reactor technologies. This can be very important in minimizing the cost of development since development of a completely new reactor would be more costly. It can also be important because of the possibility of reduction of costs to the Air Force through a common reactor program shared with the other military services.

An additional benefit of use of the NERVA derivative gas cooled reactor is that of a reduction in the impact of nuclear aircraft reactors on the nation's uranium resources. In-house Westinghouse studies have shown that an adaption of the commercial TRISO coated fuel bead in extruded graphite NERVA derivative fuel elements is appropriate. A peak burnup capability of 50 percent (compared to 25 percent in the Fort St. Vrain and 75 percent in the large HTGR commercial reactors) is well achievable. This higher burnup capability than that predicted for a liquid metal cooled NuERA type of reactor results in on the order of 60 percent less U_3O_8 raw material required per core.

Another desirable characteristic which was predicted for that Bi-Brayton system was that of some reduction in propulsion system weight. This preliminary study has indicated essentially the same total propulsion system and JP fuel weight as for the Reference 1 aircraft derived with a liquid metal cooled NuERA nuclear

TABLE 5-4

COMPARISON OF POWERPLANT CHARACTERISTICS

	REF IADS, TASK II	BI-BRAYTON
NUCLEAR SUBSYSTEM (NSS)		
REACTOR TYPE	LMCR, NUERA	GCR, (NERVA DERIV.)
REACTOR EXIT TEMP - °F	1800	1800
COOLANT	LITHIUM 7	HELIUM
MATERIALS	REFRACTORY	SUPERALLOY
NSS DIAMETER - FT.	18.3	20
INTERMEDIATE		
SEC. FLUID	NAK 78	HELIUM
IHX	LI/NAK	HE/HE
IHX TEMP - °F	1800/1700	1060/990
IHX MATERIAL	REFRACTORY	STAINLESS STEEL
PIPING OD - IN.	17.7 AND 21.1	18
PIPING FLUID TEMP - °F	1700/1300	990/120
PIPING MATERIAL	HAYNES 188	LOW ALLOY STEEL
ENGINES		
TYPE	DUAL MODE TFE	DUAL MODE TFE
NUCLEAR POWER INPUT	REPLACE COMBUSTOR	HE POWER TURBINE
EHX	NAK/AIR	HE/AIR
EHX TEMP - °F	1700/1600	720/200
JP T.O. TIT - °F	1873	>2400

propulsion system. However, since this study did not include optimization of the reactor and shielding, but instead utilized the results from other Westinghouse funded in-house studies for light weight marine applications, it is clear that weight reductions would be shown if these optimizations were accomplished. A propulsion system weight reduction of ten percent (75,000 pounds) appears to be achievable. One area in which weight reductions are expected is in the area of the "plug shield" for shielding of the piping penetrations through the shield. Alternate configurations have been identified which would provide adequate shielding at lower weight, but additional study would be required to confirm the benefits. The study results therefore confirm the viability of the Bi-Brayton system as a new alternate with the probability of some reduction in powerplant weight.

As discussed in the Reference 1 cycle comparisons, the use of separate engine systems during nuclear operation and during JP fuel operation is attractive. The reason for attractiveness is that a separate JP fuel open cycle engine does not have to be compromised by the necessity to limit turbine inlet temperature during JP fuel operation to be compatible with temperature achievable from a nuclear energy source. Thus, energy conversion by a closed Brayton system during nuclear operation frees the open cycle JP engine to make full use of available high turbine inlet temperature capabilities to minimize JP fuel carried for take-off, landing and emergency cruise. This characteristic not only minimizes aircraft weight but also helps to minimize the development required.

As part of the overall study, parametric studies were accomplished. In additon to providing input to selection of the reference Bi-Brayton system, the parametric studies have led to an overall assessment that the overall system characteristics and weight are not highly sensitive to the individual component performances. Stated another way, relatively broad latitude exists to modify the system, if found necessary, without grossly affecting total system characteristics. Feasibility and practicality of the system does not depend upon achievement of extreme component performance levels. This can be of importance in minimizing development program costs.

This study also investigated the concept of a containment vessel which could be wholly or partially removed during wartime where crash safety issues may be secondary to mission accomplishment with maximum capability. The fundamental concept of considering what modifications might be acceptable in wartime to maximize military capability appears to be highly appropriate. Methods of providing for removal of most of the containment vessel were defined. However, it does not appear that removal of the containment vessel is attractive. The requirements placed upon the containment vessel to survive crash are severe which limit the design latitude. The identifiable concepts to allow removal require longer time for removal than would seem to be desired in wartime and would probably negate the value of increased payload. Thus, although it appears that at least a major portion of the containment vessel could be made removable, it does not appear to be desirable. However, the concept of providing characteristics necessary in peacetime but of quickly altering them in wartime appears to have potential for significant enhancement of military capability. Several other alternatives have been identified and may be worthy of further study in the future. At least the possibility of enhancement of capabilities in wartime should be recognized in evaluations of the worth of nuclear powered aircraft.

The evaluations have shown that the Bi-Brayton system concept is a feasible system concept which eliminates the need for a high temperature heat exchanger and which has the potential to allow reductions in aircraft take-off gross weight. However, these studies have by design been scoping in nature and further studies are needed to optimize the concept and its critical components. Some of the critical areas which should be studied to provide a data base comparable to that existing for other systems are:

(1) Reactor optimization for the Bi-Brayton aircraft propulsion system application.

(2) System optimization studies to minimize weight.

(3) Shielding optimization, including consideration of a plug shield versus spiral piping and versus location of turbomachinery inside the shielding.

(4) Reactor and system configuration for lowest costs consistent with the aircraft application.

(5) Further turbomachinery design definition.

(6) Component mounting within the containment vessel, including arrangement to minimize containment vessel diameter.

(7) Cost evaluations for comparison with IADS Task II cost comparisons.

(8) Aircraft optimization to make full use of Bi-Brayton System characteristics.

(9) Post-impact safety studies (similar to the Reference 12 studies for the Nu-ERA system).

6.0 REMOVABLE CONTAINMENT VESSEL

The primary function of the Nuclear Subsystem (NSS) containment vessel is to ensure protection of the general public from radioactive material release even in the event of an aircraft accident. Containment vessel impact tests have been performed by both the Air Force and NASA and design correlations developed. Safety analyses of post-impact conditions have also been accomplished for the Air Force and NASA. All of these studies give confidence that the necessary containment vessel can be developed. However, the severity of the requirements results in a heavy vessel whose weight is an important fraction of the total system weight.

In time of war, the greatest danger to the populace could come from the enemy. It is therefore reasonable to consider what peacetime protection features might be removed and still provide the necessary wartime safety while enhancing military payload of the aircraft. During the Innovative Aircraft Design Study (IADS), Task II, the possibility of a removable containment vessel was identified by the Air Force but not investigated. Because of its potential, an examination of the concept was included as part of this study. For evaluation of the concept, the IADS, Task II, reference aircraft and its powerplant were used as a basis. In that aircraft the payload is 400,000 pounds and the containment vessel weighs 99,500 pounds. Clearly, a significant improvement in paylaod capability might be achieved if the containment vessel could be removed.

The design constraints placed upon the containment vessel (Table 6-1) were considered in the evaluations. The function of a containment vessel imposes severe mechanical and thermal demands on its design. It must not rupture under loads which far exceed the elastic limit and it must contain very high temperature materials after deformation without rupturing. For the mechanical requirements, it should be ductile and as devoid as possible of stress raisers. Any significant weight additions to allow removal of the vessel would detract from the suitability of a concept because those weight penalties would subtract from the peacetime payload capability of the aircraft. For the purposes of the study, it was assumed that the aircraft center of gravity could be suitably maintained either

TABLE 6-1

FUNCTIONS OF THE CONTAINMENT VESSEL

- Barrier Against Release of Fission Products
  - In Event of Rupture of Primary System Piping
  - In Event of Aircraft Crash
    - Positive Closure of Penetrations
    - Survive Crash without Rupture
    - Survive Post-Impact Heating without Rupture
- For Liquid Metal Cooled Reactor, must Prevent Air In-Leakage
- Provide Part of the Shielding (Gamma) Function
- Mounting for Internal NSS Components

through location of the NSS near the CG or through proper distribution of cargo. However, this would be a design constraint placed upon the aircraft. It was also assumed that the lost time during removal must be as short as possible, on the order of a few days at most, or else the payload benefits would not equal the payload capability lost while the aircraft was out of commission.

Several concepts were identified initially but were found to be unsuitable for one or more reasons. In essence the requirement to maintain containment integrity in a crash at velocities up to 250 feet/second eliminates most concepts because it does not appear that their survivability could be assured or they would add too much weight in the peactime version. For instance, any demountable construction such as marmon clamps, bolted flanges, etc. could not be uniformly flexible and so would have to be substantially stiffer and stronger than the walls with generous blending to the normal wall thickness. A fair estimate is that such a design could add 30 to 50 percent to the original weight, substantially cancelling any payload increase which was the original objective. The alternative is to leave the original design alone but arrange to cut parts of it away. Oxygen flame cutting would be an economical procedure for separating the sections except that the Haynes 188 alloy of the reference vessel is not practical to flame cut. Further, the functional requirements of oxidation resistance and high temperature strength essentially ensures that no satisfactory material could be flame cut.

Two concepts were identified which appear to have promise. There would seem to be no technical reason why a containment vessel could not be designed so that the major protion could be removed by machining. All penetrations would have to be confined to as narrow a diametral band as possible. If this band could be held to eighteen inches, approximately 93 percent of the containment weight could be removed by machining away the two remaining sectors. The machining could be done by a portable special cutting machine such as is now used for cutting seal welds on reactor vessels but designed for heavier cutting. Figure 6-1 is a schematic representation of such a system. The narrow band of penetrations would preferably be vertical and perpendicular to the fuselage centerline. Structural connection to the airframe would be chiefly at the bottom with horizontal support at the top designed to be flexible vertically in order to minimize thermal stress.

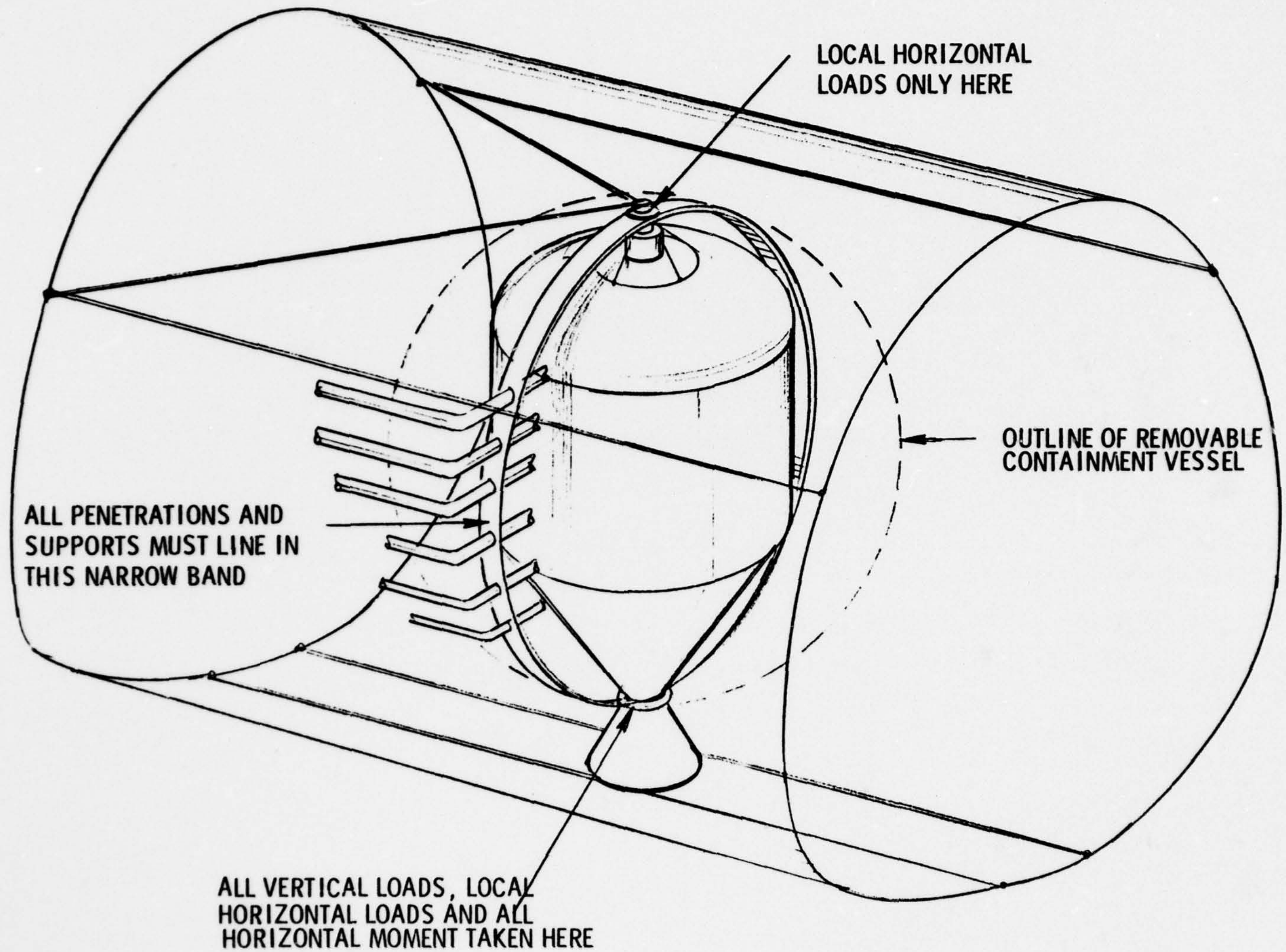

Figure 6-1. Nuclear Bi-Brayton System for Aircraft Propulsion

Thermal stress considerations in the penetrations would not be any different because of the removable feature. It appears that the peacetime weight penalty of this concept could be kept acceptably low through proper design. Two problems could be in getting the cutting machine to the vessel and in removing the cutaway sections from the airframe. It appears that the accessibility which would normally be provided to allow NSS removal for refueling would probably be sufficient, or could be modified sufficiently, for these operations. However, in spite of the probable technical feasibility of this arrangement, the turn around time to accomplish the containment removal cannot be optimistically estimated at less than a week and could easily be two or three. The strategic effect of the long turnaround time must be evaluated against the value of the increased payload.

Another concept was identified which should reduce the turnaround time. A mechanical joint with a cross section as shown in Figure 6-2 could probably be designed to meet the requirement of integrity under severe plastic deformation. The connection consists of both an external and internal tapered thread on each mating part plus a canopy seal weld. The connection would be located adjacent to the band of penetrations where the former arrangement was machined. The manufacturing and assembly problems of this design are formidable but if the socket were made in two pieces and later welded as shown in phantom, it is probable that these problems could be solved. Such a joint might reduce the turnaround time by about six days and the handling problems would be essentially the same as in the first concept.

It therefore appears that a removable containment vessel could be designed and developed which would allow 75,000 to 90,000 pounds to be removed to increase wartime payload capability. The peacetime weight penalty for the removable feature would probably be on the order of 10,000 pounds. An additional penalty would be that two to seven days would be required to effect the removal.

There is an additional consideration which must enter into evaluations of containment removal. The containment vessel also functions as part of the shielding. The containment vessel attenuates the secondary gammas by approximately one order of magnitude. As stated in Reference 6, the secondary gammas contribute 3.1 mr/hour of the allowed dose rate of 5 mr/hour. Thus, as a first

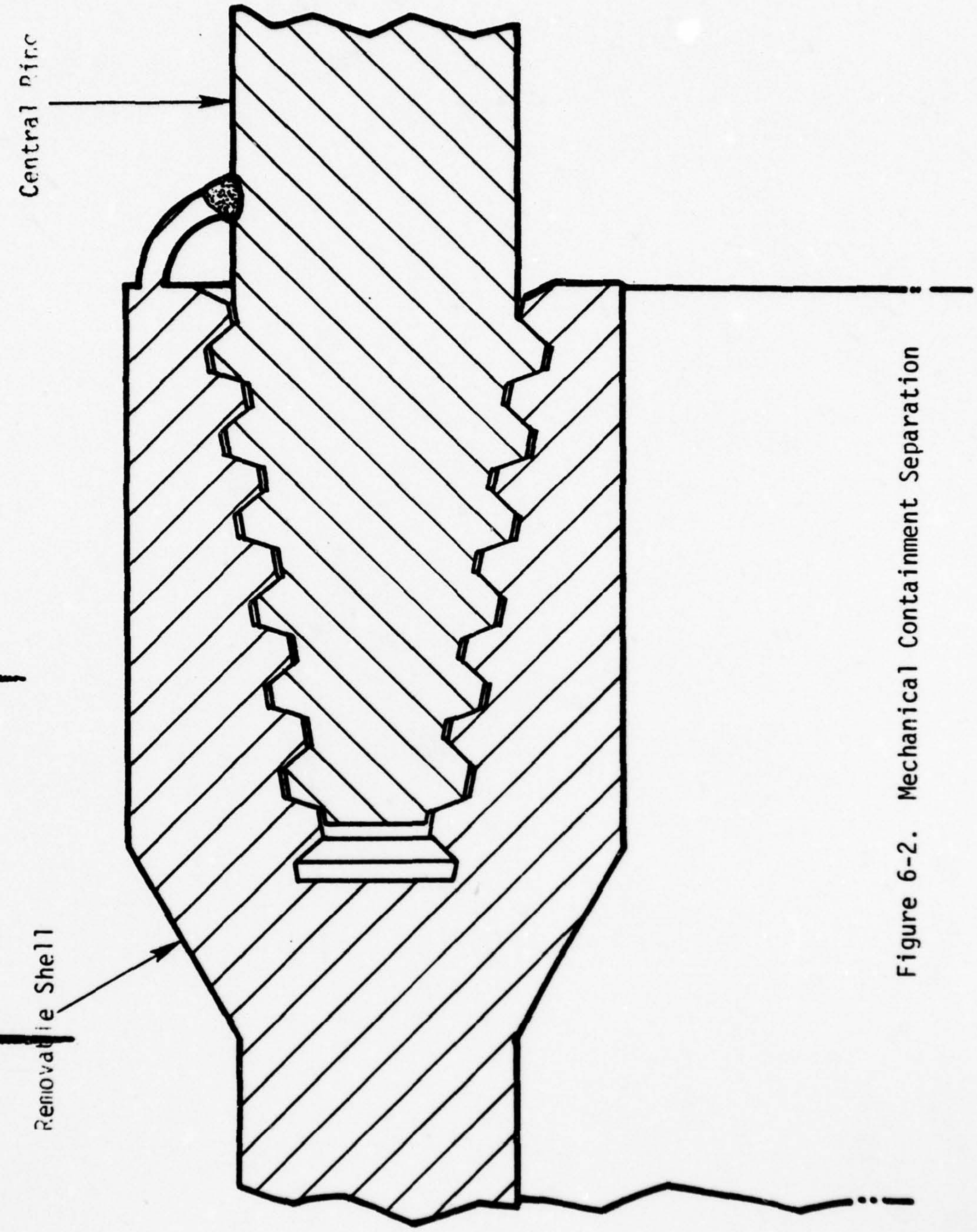

Figure 6-2. Mechanical Containment Separation

approximation, removal of the containment vessel would increase the dose rate to approximately 32 mr/hour. In order to reduce the dose rate, additional shielding would have to be installed. Even if a higher dose rate were allowed during wartime, which is not certain, some additional shielding would undoubtedly have to be installed which would remove much of the weight benefit of containment removal.

Although it appears that a removable containment vessel could be designed and developed, when all factors are considered, the potential for weight savings does not appear to be sufficient to warrant the increased complexity and the time to accomplish the removal.

However, this does not mean that the fundamental idea of wartime modifications to enhance capability is wrong. That concept appears to have merit and some consideration was given to identification of other means of reducing weight.

One possibility would simply be operational through the use of the nuclear powerplants during takeoff and landing to reduce the amount of JP fuel which must be carried for these operations. Another possibility is the reduction of the emergency fuel carried on board. In the Reference 1 study this fuel totaled 95,000 pounds to provide the capability for 1000 miles cruise without nuclear power. During wartime a smaller quantity might be carried and reliance placed upon air-to-air refueling or upon at least partial power from the nuclear system. Design of the NSS to make the probability of complete loss of power acceptably low is reasonable. The situation is not fundamentally different from that of a man-rated nuclear rocket. The reliability requirement placed upon the NERVA nuclear rocket engine, with confidence that it was achievable, was a 0.995 probability at 90 percent confidence level that the engine would successfully fullfill the endurance requirements while meeting all mission related requirements. It was also a requirement that the engine allow operation in a "malfunction mode" at reduced power in the event that a malfunction should occur so that the mission could be safely aborted. A similar philosophy of system design to minimize the consequences of malfunctions, high component reliability, redundancy and "malfunction mode" operation could be counted on to allow a reduction in emergency JP fuel carried on board.

Another possibility involves a modification to the shielding requirement. For the Reference 1 and all recent studies, the shielding requirements have included crew protection (5 mr/hour 20 feet in the direction of crew spaces during operation) and protection of ground crew (5 mr/hour in any direction 30 minutes after shutdown). The post-shutdown criterion sizes the side, top and bottom shielding. In essence the ground crew protection shielding is carried throughout the mission when it is not needed. If this criterion were relaxed and the ground crew protection shielding kept at the bases for fitting to the aircraft after landing, onboard shielding weight could be reduced. Payload could be increased or a smaller aircraft could provide the same payload capability.

Limited study has identified these possibilities which appear to have promise. It is reasonable to expect that further study would identify others. Thus, it appears that considerations of the worth of nuclear powered aircraft could reasonably assume that payload could be increased under wartime conditions.

7.0 TECHNOLOGY DEVELOPMENTS REQUIRED

The concept of the Bi-Brayton system was derived specifically to minimize the technology developments which would be required for a nuclear aircraft propulsion system. The concept was derived such as to make maximum use of technologies which have already been developed. Therefore, the technology developments which are required for the Bi-Brayton system are significantly reduced compared to other types of aircraft nuclear propulsion systems which have been studied in recent years.

In this section of the report, the technology developments required are identified and briefly discussed. Although the studies to date are sufficient to identify and generally scope the developments required, exact definition of development needs requires more detailed design studies and trades between alternatives. Also included in this section are discussions regarding the prospects for the needed developments to occur without specific USAF development efforts and assessments of the overall Air Force efforts required.

The requirements placed upon a nuclear aircraft propulsion system are quite constraining. Furthermore, the aircraft by definition will be large with large engines. These facts, plus the extreme reliability and safety requirements, mandate a comprehensive and complete development program to completely prove components and systems prior to flight. Thus, even though the fundamental technologies exist, developments are required to adapt proven technologies to the specific needs of the aircraft propulsion application, and then to prove the propulsion system as being ready for flight use.

7.1 NON-NUCLEAR SUBSYSTEM DEVELOPMENTS REQUIRED

Several features distinguish the Bi-Brayton systems from the other types of systems that have been studied for aircraft nuclear propulsion. It is in these features that the required non-nuclear subsystem developments differ from those

required for other types of powerplants. In general, the development problems are eased, but not eliminated. Table 7-1 lists the more significant items.

7.1.1 Turbomachinery

Compact closed cycle Brayton turbomachinery will require development even though other programs can be expected to provide much of the technology that will be needed. Compactness, particularly in length, is obviously necessary for the Bi-Brayton turbomachinery because of the need to minimize the containment vessel diameter and weight. High primary system compressor and turbine efficiencies are not quite as important in the Bi-Brayton system as in other closed Brayton cycles, since the reject heat is utilized for thrust, but are still important. These considerations may lead to a desire to incorporate high reaction compressor blading to minimize the compressor length. Similar design and development considerations apply for the secondary system compressor. It appears that cooling will be required for the primary system turbine blades, or use of ceramic or refractory materials. This study has assumed the use of cooled turbine blades. In any event, development will be required for this high temperature turbine. Gas bearings are desirable for this application, although not mandatory. As shown in Reference 7, the technology exists for the needed gas bearings, but development efforts are required for the sizes and requirements of this application.

The need to separate the primary and secondary flows from each other will require specific development of highly reliable shaft seals. These seals must provide effective sealing during system operation and during shutdown conditions. A representative sealing concept was derived as part of this study, but it is recognized that some seal development must be planned as part of the turbomachinery development.

The power turbines located in each nacelle can be likened to the power turbine in the typical closed cycle Brayton system. No major problems are foreseen for the power turbine, but some development efforts peculiar to the aircraft application will undoubtedly be necessary.

TABLE 7-1

NON-NUCLEAR

TECHNOLOGY DEVELOPMENTS REQUIRED

- Compact Closed Cycle Brayton Turbomachinery
- Fan Drive Power Turbine
- Reduction Gear and Clutch
- Compact, High Effectiveness Intermediate Heat Exchangers (helium-to-helium, T max = 1060°F)
- Compact, High Effectiveness Exhaust Heat Exchanger (helium-to-air, T max = 722°F)
- Piping and Valves
- System Integration and Optimization

The Bi-Brayton system turbomachinery development program can be expected to make extensive use of technology developed in past and future closed cycle Brayton system programs. Of particular value would be the technology resulting from a Navy program to develop a compact closed cycle Brayton system for ship propulsion. The compressor, turbine, bearing, seal etc., technologies from such a Navy program would be directly applicable to the needs of the USAF Bi-Brayton system. However, the aircraft application will place unique requirements on the turbomachinery. Therefore a specific USAF development program will be necessary, but the magnitude of the program could be significantly reduced through technology contributions from other programs.

As discussed in Section 5.2, a reduction gear assembly is required between the power turbine and the fan. Also required is a coupling which allows either the helium cycle turbine or the air cycle engine, or both, to drive the fan. As discussed in Section 5.2, these components have been defined and sized based upon adaptations of proven designs. The developments foreseen for these power transmission components are associated with translation of existing technology into designs to meet the specific needs of the Bi-Brayton system. It is therefore unlikely that other programs outside the USAF would provide the developments needed over and above the technology which already exists for these components.

Technology developments for the air cycle engine are not listed in Table 7-1 because the Bi-Brayton system concept does not require that the air cycle gas turbine operate on nuclear power. Therefore, air cycle engine developments to operate at lower turbine inlet temperature and increased mid-section pressure drop are not required. Conventional engines of appropriate size can be used.

7.1.2 Heat Exchangers

Probably the greatest differences of the Bi-Brayton system from others are in the temperature levels which the primary-to-secondary and the secondary-to-air heat exchangers must operate. In the Bi-Brayton system the primary-to-secondary (intermediate) heat exchangers are only exposed to 1060°F instead of 1800°F. This significantly eases the design problems through allowing greater latitude

in material selection and in the higher capabilities of materials at the lower temperature. However, the Bi-Brayton intermediate heat exchanger requires specific development efforts. Its installation inside the NSS containment vessel requires that it be as small as practical, particularly as short as practical, since the length can effect the containment vessel diameter. The location inside the containment where access for maintenance is difficult, requires that it be highly reliable. In addition, these heat exchangers must include large heat transfer surface areas which could lead to high expense unless particular attention is paid to design and development for minumum cost. Therefore, although the lowered temperatures and the use of inert gas working fluids significantly eases the problems, specific developments are requred for the intermediate heat exchangers and are indicated in Table 7-1.

Some of the development necessary for the intermediate heat exchanger may occur without specific USAF development efforts. The requirements placed upon the intermediate heat exchangers are very similar to those placed upon the recuperator in a compact closed cycle Brayton system. The design of the intermediate heat exchanger could also be very similar to the design of such a recuperator (Reference 7). Therefore, if a compact closed cycle Brayton system is developed for Navy use, much of the development that would be necessary for an aircraft Bi-Brayton system would be accomplished. However, there would still be some development required by the USAF in adapting the technology and proving the heat exchangers for an aircraft Bi-Brayton system.

7.1.3 System

Several system technology developments are also required. Use of concentric hot-leg and cold-leg piping in the secondary system is important in minimizing system weight. Concentric piping also is important in maximizing practicality because such a piping arrangement maintains the hot-leg piping material temperature at low levels. Such piping has been used in numerous installations in the past, but the requirements associated with use in an aircraft application will require some additional development. Developments peculiar to the aircraft

system include the need to design for light weight and to accommodate the flexing of the wings. In order to minimize energy loss from the hot-leg, a thin liner to provide a stagnant gas insulating layer is desirable, the integration of which into the piping design will require some development.

Closely related to the piping developments are the valves. Although no control valves are required directly in the hot or cold-legs of the secondary system, shutoff valves for each engine are necessary. These valves must be light weight and provide as tight a seal as practical under high ΔP conditions. The necessity to install these valves in concentric piping requires special configurations. Inventory control valves and/or compressor bleed valves do not have to be installed in concentric piping nor do they have requirements for extreme leak tightness, but they do have requirements for light weight and for operation in an unusual environment.

The lower temperature and the use of helium as the working fluid instead of liquid metal significantly reduces the development required for the Bi-Brayton secondary system, compared to other types of nuclear systems for aircraft propulsion. However, as discussed above, some developments are required for piping and valves because of the special requirements. These requirements and the secondary system concentric piping configuration are unique to the nuclear aircraft application and there is little likelihood of the necessary developments being accomplished except by the Air Force.

This current study has served to define the Bi-Brayton system and to provide an overall evaluation of the suitability of the concept. These results combined with the results from other past studies of nuclear aircraft propulsion systems provide information necessary for consideration of the concept. However, additional studies are required to optimize the system and components. Detailed system integration and optimization is therefore required early in the development program to establish the detailed component requirements. Then developments can proceed in a manner which will result in the necessary system characteristics being achieved. This initial system optimization and integration effort should include consideration of the range of requirements placed upon the propulsion

system by aircraft and should consider in detail the component technology capabilities extent. Through trade-off studies, the overall system can then be defined in detail to provide the necessary capabilities and characteristics while minimizing the development needs.

An important effort that must also be planned is that of a continuing system integration and optimization in parallel with the technology development efforts. The Bi-Brayton system as currently conceptually defined should undoubtedly be modified to enhance its characteristics and to minimize the component developments required. The Bi-Brayton system appears to provide broad latitude for trade-offs of the component requirements such as to minimize development needs. A system integration and optimization effort conducted in parallel with the early component technology development efforts can make a significant contribution by reapportioning component requirements where found to be desirable as technology development results become available.

7.2 NUCLEAR SUBSYSTEM DEVELOPMENTS REQUIRED

Although design definition of the Nuclear Subsystem was not part of this study, a brief discussion of its development needs is desirable for completeness. Table 7-2 lists the more significant technology developments required.

The compact gas cooled reactor concept has been derived from the proven technology of the NERVA nuclear rocket reactor and from the commercial gas cooled reactors. Thus the reactor developments that are necessary are primarily those associated with adaptation of existing technology rather than development of new technology. This fact minimizes the uncertainties and also helps to minimize the costs of development. However, an extensive program must still be planned to design and prove the reactor because of its importance and because of the stringent operational and safety requirements placed upon it. The reactor development program is envisioned to include design and analysis, component tests, reactor tests and complete engine tests.

TABLE 7-2

NUCLEAR

TECHNOLOGY DEVELOPMENTS REQUIRED

- NERVA Derivative Compact Gas Cooled Reactor
- Light Weight Layered Shielding
- Weight Optimized Plug Shielding (or alternate) Configuration and Materials
- Crash Survivable Containment Vessel
- Containment Vessel Penetration Shutoff Valves
- Nuclear Subsystem Auxiliary Systems
- Nuclear Subsystem Optimization as a Part of the Overall System

The need for light weight shielding is common to all types of reactors which might be considered for aircraft. Its importance is clear when it is recognized that the shielding makes up approximately 50 percent of the total propulsion system weight. In this study, the weight optimized layered shielding defined in the Reference 6 NuERA studies has been used. Shielding development should include measurements of the effectiveness of the various materials separately and in combination with each other. Development should also consider other candidate materials which have the potential for reducing system weight and/or system cost.

The shielding development program will also need to derive the shielding necessary for the piping penetrations. The concept utilized in this study assumed the relatively heavy design solution of a "plug" shield in the lines. Other lighter configurations are also possible, but their suitability must be proven. Because the form of the piping penetration shielding is very important to system weight, specific analytical and experimental developments should be planned to optimize configuration and materials and to prove the shielding effectiveness.

Auxiliary systems, such as shutdown cooling, shield cooling and others, will require some development to assure suitability while minimizing weight. No major problems are foreseen, but development efforts must be planned as part of a complete program.

As discussed in References 3, 4, 5, 13 and 14, in-house Westinghouse studies have shown that there can be a high degree of commonality in development of light weight reactors for various mobile nuclear powerplant applications. This introduces the possibilities that an Air Force reactor development program could be shared with other services or agencies, or could make use of much of the technology developed through another service's program. However, the potential benefits of commonality are not likely unless maximum practical commonality is specified at the outset and implemented throughout the reactor development program. If this is not done, research and design decisions are likely to be made in the context of only one application which could then inadvertently preclude use of the results in another application.

Complete commonality of reactors among various applications is of course not practical. What can be common is the basic technology development and to some extent even component development. The potential for commonality in multiple applications is one of the attractive aspects of the NERVA derivative reactor. Other potential applications have been shown to be marine propulsion (both high performance ships and displacement vessels), spacecraft power, and also stationary commercial powerplants (in the latter case, technologies could be common rather than component designs).

A crash survivable containment vessel has been assumed to be required in all recent studies of nuclear aircraft propulsion systems. The need for such a containment vessel and for penetration shutoff valves is therefore common to all forms of nuclear subsystems. The success of the extensive impact tests of scale model containment vessels by the Air Force and NASA give confidence that the necessary containment vessel can be developed. However, further development effort is very much determined by the extent of the safety requirements placed upon the overall system and by the apportionment of safety requirements between operational and design constraints.

As with other components of the overall system, the nuclear subsystem must be optimized as part of the overall system, and development efforts are indicated for this activity.

7.3 DEVELOPMENT COSTS

Estimates of development costs are necessarily uncertain before specific technical, safety and programmatic requirements have been defined. However, past light weight nuclear powerplant development programs can provide useful input to judgments regarding development costs. Two programs in particular are useful because they were carried relatively far through the development process and because they were technically successful. These programs were the Aircraft Nuclear Propulsion and the nuclear rocket programs. Review of the costs of those programs, the developments they accomplished compared to that which would be required for a Bi-Brayton aircraft system, and adjusting for the dollar inflation

since those programs were terminated, results in an approximation that is probably reasonable. These considerations indicate an approximate development cost of 1.75 billion dollars, plus approximately 0.5 billion dollars for development facilities, all in 1977 dollars. Of these costs, probably 50 percent might be borne by the Air Force and 50 percent by the Department of Energy.

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